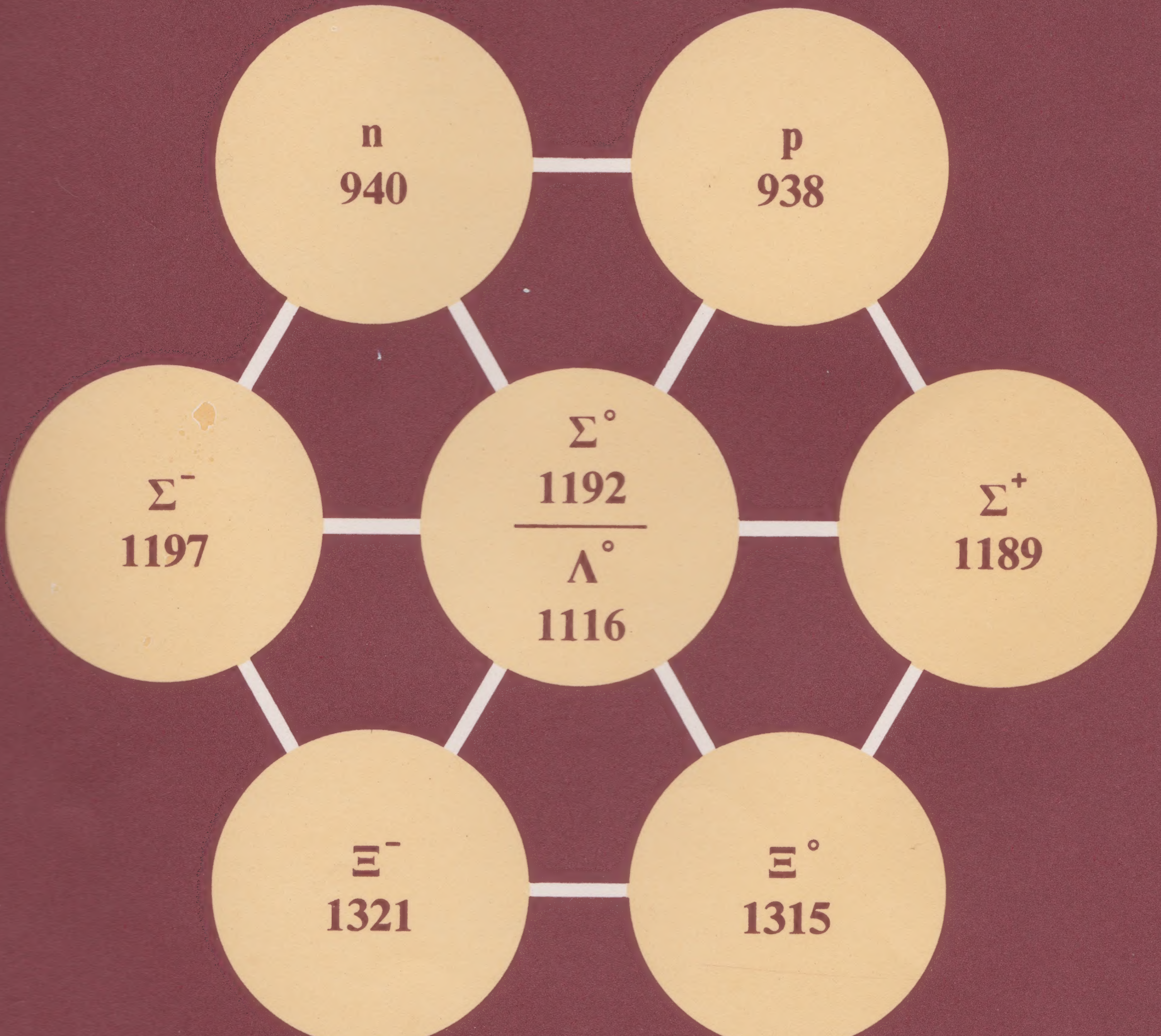
S101 Unit 31

THE OPEN UNIVERSITY

Science : A Foundation Course

The Search for Fundamental Particles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The Open University

Science: A Foundation Course

Unit 31

The Search for Fundamental Particles

Prepared by the Science Foundation Course Team

The Open University Press

SCIENCE

S101 Course Team List

A note about the authorship of this text.

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* Summer School.

Study guide

This week's work concludes your study of modern physics, which started with Unit 29, where you learned about quantum theory, and continued through Unit 30, where you learned how to apply quantum theory to the structure of atoms and nuclei. In this Unit you will learn about the structure of the protons and neutrons, which make up nuclei.

Your study of *the search for fundamental particles* includes the following:

1 Studying the Main Text of Unit 31.

2 Watching TV Programme 31 and studying the *Broadcast Notes.*

3 Studying bubble-chamber stereophotographs, in the Audio-visual sequence outlined in Section 5.7 of the Main Text.

4 Making patterns of particles using the special counters and graph paper provided for this Unit, following the instructions in Section 6.1 and 6.2 of the Main Text, which are backed up by help on audio cassette.

5 Answering the CMA and TMA questions for Unit 31.

There are many new ideas in Unit 31, so it is particularly important to be guided by the SAQs and Objectives, which indicate what you are expected to achieve this week. Please note that you are *not* expected to remember the names and properties of the many particles you will encounter. Nor are you expected to remember details of the experimental techniques used in the search for fundamental particles. You might also like to know that most of the mathematics you will be using this week is very simple: it mainly involves adding or subtracting numbers less than or equal to 3!

In the television component of the Unit (TV31) we show how the main ideas of Sections 5–9 of the Main Text link together. If you watch the programme before studying these Sections it should serve as valuable preparation and whet your appetite for the Main Text. If you watch the programme during your study of these Sections, it should reinforce the ideas in the Main Text and give you new insights. In either case, you should be able to appreciate why physicists are so excited by the ideas of 'quarks', 'strangeness' and 'charm'.

In Section 5.7, you will need the stereoviewer, Filmstrips 31.1 and 31.2, and audio cassette AC195 for the Audio-vision sequence entitled 'Bubble-chamber photographs'. We hope you will enjoy 'looking into a bubble chamber' and seeing visual evidence for some of the processes you will have learnt about by then.

There is a sheet of card, entitled 'Assorted hadrons for Unit 31', and three sheets of special graph paper, mailed with this Unit. These are the materials you need, in Sections 6.1 and 6.2, to discover the patterns made by particles. The instructions on how to use them are included in the Main Text. But if you encounter any problems in making these patterns you will find expanded instructions and helpful hints on audio cassette AC89 in the Audio-vision sequences entitled 'Hadron families' and 'Making the patterns'. If you can succeed in making these patterns first time round, there is no need to listen to the cassette.

Finally, be sure to do ITQs 14–20 in Section 7.1. There you will be able to make your own predictions about a new particle. We hope that you will arrive at the same conclusions reached by a theoretical physicist, Murray Gell-Mann, in 1962. Gell-Mann was awarded the Nobel Prize for Physics in 1969.

1 Introduction

In this Unit you will learn some of the most recent answers to some of the oldest scientific questions asked by man:

> What is matter made of?
>
> How many types of building block are needed, and how do they combine, to produce the diversity of form so apparent in the world?
>
> What more is there to learn about the structure of matter and how can it best be discovered?

The answers we shall give are at best tentative and may well change as dramatically in the next few decades as they have in the last few. But there are three good reasons why we feel they make a fitting end to your study of the physical sciences in this Course.

First, we feel that having come so far you deserve to learn a little about the latest chapter in the continuing story of man's quest for *order* and *unity* amidst variety and diversity. You already know how living organisms—the most diverse and complex structures known—are united at the macromolecular level by the way the genetic traits of every individual are encoded by four simple chemical bases in the molecules of DNA. You have also seen how chemists have realized the ancient hope of understanding the diversity of all known substances in terms of a much smaller number of elements and you know that the properties of these hundred or so elements can be understood in terms of the electronic configurations of atoms. Finally, in the last Unit, you saw how the diversity of atomic nuclei can in turn be understood in terms of the way protons and neutrons combine. In this Unit you will discover that the story has at least one more chapter. At the subnuclear level there is yet more diversity to be found and unity to be sought.

Secondly, we are adding the latest chapter in the story of *energy*. In the last Unit you saw how one of man's oldest dreams—the transmutation of elements—is achieved in the phenomena of radioactivity and fusion. In such processes the changes in energy are roughly a million times greater than those in chemical processes. In this Unit you will learn about something even more dramatic—the creation and decay of *new* types of particle, associated with even higher energies.

Finally, we feel your study of the physical sciences in this Course will be truthful to man's continuing scientific quest only if it ends on a note of *uncertainty*. It should already be clear to you how much more remains to be understood and explained in the *Earth* and *life* sciences. We hope that by the end of this Unit you will appreciate that there are many important and unanswered questions in the *physical* sciences that are being tackled today in the same spirit of enquiry that informed the study of the planets in the seventeenth century and the study of atoms in the first half of this century. Of all the Units of S101, this one contains the most science that could not have been taught to a student of S100, because it was not known in 1971. By the same token, a student of S102 will be better placed than *you*, by virtue of the scientific work going on at this very minute in laboratories and universities throughout the world.

2 What is a fundamental particle?

A fundamental particle is a particle that is not believed to be made of simpler particles. A cricket ball is *not* a fundamental particle, because it is believed to be made of various types of molecule. A molecule is *not* a fundamental particle, because it is believed to be made of atoms. An atom is *not* a fundamental particle, because it is believed to be made of subatomic particles: electrons and an atomic nucleus. An atomic nucleus is *not* a fundamental particle, because it is believed to be made of subnuclear particles: protons and neutrons. But are electrons, protons and neutrons fundamental particles? That is the sort of question which is involved in the search for fundamental particles and you will see that it is not a simple question. The answer depends upon how much is known and understood about the structure of matter at the extremes of smallness. As new experiments are performed and new models devised, the answer may change.

fundamental particle

subatomic particle

subnuclear particle

ITQ 1 Make a list of all the particles*, mentioned so far in the Course, that might be regarded as fundamental, on the basis of what you have learnt so far. Does it follow that all these particles are regarded as fundamental by modern physicists?

In this Unit you will discover that protons and neutrons are *not* regarded as fundamental particles by modern physicists. They are believed to be made of simpler particles called *quarks*. But electrons and photons *are* regarded as fundamental particles; there is no indication, as yet, that they are made of simpler particles.

3 More failures of Newtonian mechanics

In Unit 3 you learned about Newtonian mechanics, which gives a very good description of the behaviour of bodies of everyday size, travelling at everyday speeds. In Unit 29 you learned that the behaviour of individual electrons reveals quite new effects: the wave-like properties of subatomic particles require a new theory, called quantum theory, to describe them. In Unit 30 we used simple features of this theory to explain some of the properties of atoms and nuclei. In this Unit we shall describe how physicists have tried to probe even deeper into the structure of matter, analysing the neutrons and protons from which nuclei are made.

To learn about the structure of matter on a very small scale you have to bombard it with particles of very high energy. To understand why this is so, consider for a moment how scientists have learnt about various sorts of structure. Biologists have learnt about microscopic organisms using visible light, whose wavelength of about 5×10^{-7} m is small enough to reveal their structure. But the molecular structure of DNA was discovered only by using X-rays of much smaller wavelength. Physicists have learnt about the structure of crystals using X-rays and using beams of electrons with de Broglie wavelengths that are even smaller still. Rutherford and Chadwick discovered the existence and approximate size of atomic nuclei by bombarding matter with α-particles of even smaller de Broglie wavelength. To learn about the microstructure of matter, at the extremes of smallness, physicists must use *particles whose de Broglie wavelengths are as small as possible.* The formula for de Broglie wavelength

$$\lambda_{\mathrm{dB}} = \frac{h}{p} \qquad \text{(Unit 29, equation 5)}$$

shows that they must use particles of the largest possible momentum p. And since momentum increases with kinetic energy that means using particles of the highest possible energy. For this reason, the study of subnuclear particles is often called high energy physics.

high energy physics

The acceleration of particles to high energies and the study of what happens when they collide with the nuclei of matter reveal further inadequacies of the Newtonian mechanics of Unit 3, beyond those quantum effects you have studied so far. These failures were anticipated by Albert Einstein in his special theory of relativity, published in 1905. They concern the behaviour of bodies at high speeds—speeds approaching the speed of light. We are not able in this Foundation Course to describe the new understanding of space and time that resulted from Einstein's work. But there are three effects that he predicted and that have been abundantly confirmed by the studies of high energy physicists. The speed of light plays a vital role in the special theory of relativity and the reason why the effects are not apparent at the speeds we are used to in everyday life has to do with the very large value: $c = 3.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$. In the next three Sections we shall discuss these effects, giving indications of why they are important in high energy physics. But first of all it is worthwhile doing a calculation that shows how the desire to learn about subnuclear particles leads one to use particles whose speed is very far from small.

special theory of relativity

---

* Note that we continue the practice of Unit 30, by referring to electrons, photons, etc., as 'particles', rather than 'quanta', for the reason explained in Section 3.1 of Unit 30.

ITQ 2 Suppose you want to learn about the structure of nuclei by bombarding them with α-particles. You decide to use α-particles whose de Broglie wavelength is 3.0×10^{-15} m, comparable to the size of a nucleus. Use the formula:

$$\lambda_{\text{dB}} = \frac{h}{p} = \frac{h}{mv}$$

to work out what speed the α-particles must have. (The mass of an α-particle is 6.6×10^{-27} kg and $h = 6.6 \times 10^{-34}\,\text{kg}\,\text{m}^2\,\text{s}^{-1}$.) How does this speed compare with (a) the speed of light ($3.0 \times 10^8\,\text{m}\,\text{s}^{-1}$) and (b) the speed of sound in air ($3.0 \times 10^2\,\text{m}\,\text{s}^{-1}$)?

3.1 Inertia increases with speed

In Unit 3 we said that the mass of a body is related to two separate characteristics of the body: the *weight* in a gravitational field and the *inertia*, which determines the acceleration that will be produced by a given force. We now need to say a little more about the inertia of bodies travelling at speeds comparable to the speed of light, speeds that Newton never contemplated but that can be achieved using the machines which physicists and engineers have built to study subnuclear particles.

According to Newton's second law, a constant force F acting on a body of mass m will produce a constant acceleration a given by:

$$a = \frac{F}{m}$$

The acceleration should be constant, because the inertia of the body is given by its mass m, which is supposed to be an unchanging property of the body. At Stanford in California there is a machine which shows that this simple prediction of Newtonian mechanics *fails* at very high speeds. As you can see from the aerial photograph of Figure 1 it is a big machine—about 3 km long. But it does a very simple

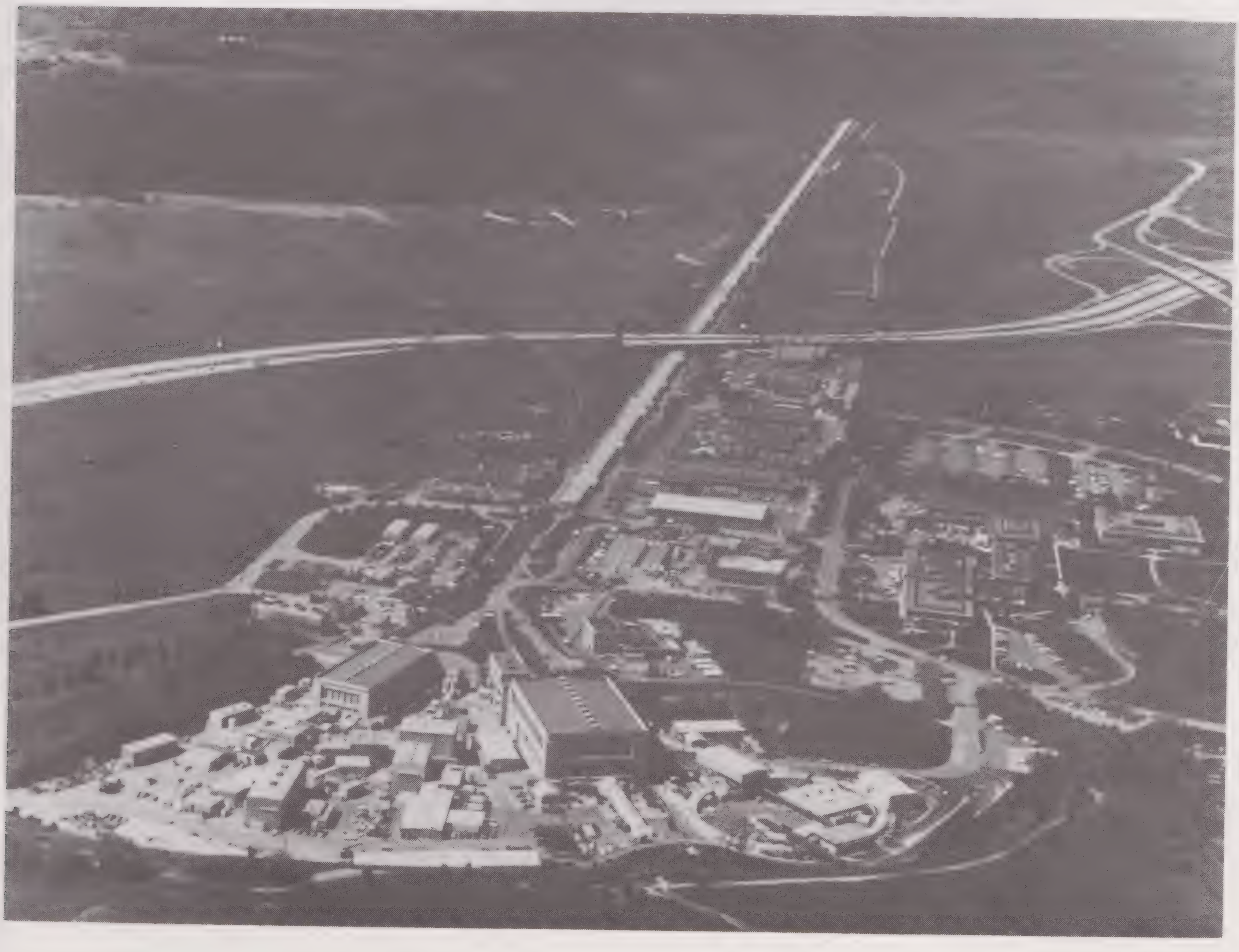

FIGURE 1 The Stanford linear accelerator.

job. Electrons start at one end and are accelerated by an electric field, gaining energy and speed, until they emerge at the other end, where they collide with a target. What happens when they collide with the target is the subject of Section 5. All we need to know now is the speed they have after being accelerated.

The electrons are accelerated by an electric field which subjects them to a constant force of 1.1×10^{-12} N. This sounds like a tiny force, but it corresponds to a potential difference of 7×10^6 V for every metre they travel. That means that in 3 km they gain an energy of

$$\begin{aligned}(7 \times 10^6) \times (3 \times 10^3)\,\mathrm{eV} &= 21 \times 10^9\,\mathrm{eV}\\ &= 21 \times 10^3\,\mathrm{MeV} = 21\,\mathrm{GeV}\end{aligned}$$

where GeV stands for giga electronvolt ($1\,\mathrm{GeV} = 10^9\,\mathrm{eV}$).

giga electronvolt GeV

What is the predicted speed of the electrons, as they emerge from the machine, according to Newton's laws of motion? The simplest way to calculate the predicted speed is to use the formula for kinetic energy given in Unit 8:

$$\begin{aligned}\text{kinetic energy} = \tfrac{1}{2}mv^2 &= 21 \times 10^9\,\mathrm{eV}\\ &= (21 \times 10^9) \times (1.6 \times 10^{-19})\,\mathrm{J}\\ &= 3.4 \times 10^{-9}\,\mathrm{J}\end{aligned}$$

The mass of an electron is 9.1×10^{-31} kg. Thus, according to Newton, the speed should be given by:

$$\begin{aligned}v^2 &= \frac{2 \times (3.4 \times 10^{-9})}{9.1 \times 10^{-31}}\,\mathrm{m^2\,s^{-2}}\\ v &= \sqrt{\frac{2 \times (3.4 \times 10^{-9})}{9.1 \times 10^{-31}}}\,\mathrm{m\,s^{-1}}\\ &= 8.6 \times 10^{10}\,\mathrm{m\,s^{-1}}\end{aligned}$$

That is surely a remarkable prediction! According to Newton's laws the electrons should emerge with a speed that is nearly 300 times the speed of light. *This prediction is very badly wrong.* In fact, the electrons have a speed that is very slightly less than the speed of light ($v = 0.999\,999\,999\,7\,c$). According to Einstein, *nothing* can travel faster than the speed of light in a vacuum.

The details of Einstein's theory are beyond the scope of this Foundation Course, but the message of this Section is very clear: the laws of Newtonian mechanics are quite inapplicable at the very high speeds and energies achieved with particle accelerators. The best way to express this failure of Newtonian mechanics is to say that *inertia increases with speed.* That means that electrons in the Stanford linear accelerator become harder to accelerate as their speed increases. At speeds approaching *c*, the effect becomes very important, as witnessed by the fact that *the electrons never reach the speed of light.*

inertia increases with speed

The increase of inertia with speed applies to all objects, at all speeds, but it is utterly negligible at the speeds to which we can accelerate large bodies, like aeroplanes or rockets. The inertia of a rocket travelling at 10 000 m.p.h. is only 1 part in 10^{10} greater than its inertia at rest*. So even NASA can use Newton's laws without getting into trouble. At present, only high energy physicists need abandon Newton's laws in favour of Einstein's.

Now check that you can recognize the limits of validity of Newton's laws, imposed by the increase of inertia with speed (Objective 1).

* The precise relationship between inertia and speed, which you do *not* need to remember, is:

$$\frac{\text{inertia at speed } v}{\text{inertia at rest}} = \frac{1}{\sqrt{1 - v^2/c^2}}$$

SAQ 1 Suppose it were possible to apply a constant force of 1 N to a mass of 1 kg for an unlimited time. When would you expect the failure of Newton's second law to become apparent? (Select *one* item from the key.)

A After one second

B After one minute

C After one hour

D After ten years

E After a hundred years

(There are about 3×10^7 seconds in one year, and the speed of light is $3 \times 10^8\,\mathrm{m\,s^{-1}}$.)

3.2 Mass is not conserved

mass is not conserved

You have already met an example of the second new effect predicted by Einstein's theory. You know that when two protons and two neutrons fuse to make an α-particle, there is a detectable *decrease* in mass, associated with the energy that is *released.*

In the postscript to Unit 30 it was shown that the release of 28.3 MeV of energy:

$$\mathrm{p} + \mathrm{p} + \mathrm{n} + \mathrm{n} \longrightarrow {}^4_2\mathrm{He} + 28.3\,\mathrm{MeV}$$

is accompanied by a decrease in mass of 5.03×10^{-29} kg:

$$2\mathrm{m_p} + 2\mathrm{m_n} - \mathrm{m_{He}} = 5.03 \times 10^{-29}\,\mathrm{kg}$$

The relationship between the energy released and the decrease in mass is given by Einstein's celebrated equation $E = mc^2$, which fixes (in banking terms) the 'exchange rate' between energy and mass:

$$\begin{aligned}\text{energy released} &= (\text{decrease in mass}) \times c^2\\ &= (5.03 \times 10^{-29}) \times (3 \times 10^8)^2\,\mathrm{J}\\ &= \frac{(5.03 \times 10^{-29}) \times (3 \times 10^8)^2}{1.6 \times 10^{-19}}\,\mathrm{eV}\\ &= 2.83 \times 10^7\,\mathrm{eV}\\ &= 28.3\,\mathrm{MeV}\end{aligned}$$

But there are a couple of questions which need answering before you can be sure of using this equation corretly: What is meant by *mass*? In what *form* is the energy released?

The first question can no longer be answered by saying that the mass of a particle is equal to its inertia. You have just seen that inertia increases with speed, but physicists like to define the mass of a particle in such a way that it is an unchanging property of the particle. So the mass of a particle is defined as its *inertia when the particle is at rest**. That means that if you subject an electron at rest to a force of 9.1×10^{-31} N it will start moving with an acceleration of $1\,\mathrm{m\,s^{-2}}$, because its mass is 9.1×10^{-31} kg and Newton's second law:

$$F = ma$$

can be used at low speeds. But at speeds close to the speed of light, Newton's second law cannot be used. The same force will produce a smaller acceleration, because inertia increases with speed and thus becomes greater than the mass.

The second question is rather simpler to answer. In what form is energy released when the total mass of particles decreases? It is released as *kinetic energy*: energy of motion. For example, the fusion of neutrons and protons in the Sun leads to a decrease of mass of 5.03×10^{-29} kg for every α-particle formed. This is accomplished in a complicated sequence of reactions, but the result is very simple: the total kinetic energy of particles increases by 28.3 MeV for every fusion, so that there is more energy of motion before than after. If the Sun did not eventually radiate this energy, it would get hotter and hotter, because the particles inside the Sun would be rushing around faster and faster. In fact, the energy released by fusion is eventually radiated, mainly in the form of light. But that too is a form of kinetic energy. You know from Units 9 and 29 that light, when it interacts with matter, behaves like a stream of particles, called photons, each of which has a kinetic energy given by:

---

* This is sometimes called the 'rest mass'. In this Course we do not bother with the extra word 'rest' because the mass here *always* means the inertia at rest.

$$E = hf \qquad \text{(Unit 29, equation 18)}$$

where f is the frequency associated with the wave-like behaviour of the light. So, provided we include the energy of photons in our accounting of the kinetic energy of particles, we can use the equation $E = mc^2$ to conclude that:

$$\boxed{\text{increase in kinetic energy} = (\text{decrease in mass}) \times c^2}$$

in processes involving the collision, fusion and decay of particles.

But this is only half of what is implied by $E = mc^2$. Einstein is an unusually generous banker. He allows kinetic energy to be converted back into mass at exactly the same 'exchange rate'. In other words:

$$\boxed{\text{decrease in kinetic energy} = (\text{increase in mass}) \times c^2}$$

in any process in which particles react with each other to form new particles whose total kinetic energy is less than you started with.

By way of a dramatic example, we shall anticipate matters a little by telling you that a new particle was discovered in 1950. It is called the neutral pion and is represented by the symbol π^0 (pi zero). All that you need to know about it now is that it can be produced when a proton from an accelerator collides with a proton in the nucleus of an atom. The reaction is:

$$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^0 - 135\,\mathrm{MeV}$$

and the minus sign indicates that there is a *decrease* of 135 MeV in the total kinetic energy of the particles involved. That means there must be an *increase* of the total mass of all the particles involved. Indeed you can see that there is. You start with two protons and end up with two protons *and* a π^0. So the increase in mass is just the mass of π^0. That means:

$$135\,\mathrm{MeV} = (\text{mass of } \pi^0) \times c^2$$

mass in MeV/c^2

So what is the mass of the π^0 particle? It is 135 MeV/c^2. Now that probably doesn't mean very much to you yet. To compare this mass with the mass of the proton ($m_\mathrm{p} = 1.67 \times 10^{-27}$ kg) we could convert the units of MeV/c^2 into kilograms. But there is another way of making the comparison. Why not express the mass of the proton in units of MeV/c^2?

We know that $m_\mathrm{p} = 1.67 \times 10^{-27}\,\mathrm{kg}$

and hence
$$\begin{aligned} m_\mathrm{p}c^2 &= (1.67 \times 10^{-27}) \times (3 \times 10^8)^2\,\mathrm{kg\,m^2\,s^{-2}} \\ &= 1.50 \times 10^{-10}\,\mathrm{J} \\ &= \frac{1.50 \times 10^{-10}}{1.60 \times 10^{-19}}\,\mathrm{eV} \\ &= 9.38 \times 10^8\,\mathrm{eV} \end{aligned}$$

So $m_\mathrm{p}c^2 = 938\,\mathrm{MeV}$

Dividing both sides of this equation by c^2 we find that the mass of a proton is 938 MeV/c^2. So the mass of a π^0 particle, 135 MeV/c^2, is about 14 per cent of the mass of a proton. Here is a process in which there has been an increase in mass of 7 per cent. If you compare this with the decrease in mass in the fusion of neutrons and protons to make an α-particle (0.8 per cent), you can see that the changes in mass we shall be considering in this Unit are significantly greater than those involved in nuclear physics.

In the remainder of the Unit we shall usually quote masses in units of MeV/c^2. Then you will be able to relate changes in mass (in MeV/c^2) to changes in energy (in MeV) without ever needing to use the numerical value of the speed of light. From now on there is not much arithmetic you need to do, beyond simple addition and subtraction.

Suppose a particle called π^+ (pi plus) is produced in the reaction:

$$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+ - 140.9\,\mathrm{MeV}$$

Given that $m_\mathrm{p} = 938.3\,\mathrm{MeV}/c^2$ and $m_\mathrm{n} = 939.6\,\mathrm{MeV}/c^2$, what is the mass of π^+ in MeV/c^2?

To solve this problem we use $E = mc^2$:

$$\boxed{\text{decrease in kinetic energy} = (\text{increase in mass}) \times c^2}$$

$$\begin{aligned}140.9\,\mathrm{MeV} &= (m_\mathrm{p} + m_\mathrm{n} + m_{\pi^+} - m_\mathrm{p} - m_\mathrm{p}) \times c^2\\ &= (m_{\pi^+} + m_\mathrm{n} - m_\mathrm{p}) \times c^2\\ &= m_{\pi^+}c^2 + (939.6 - 938.3)\,\mathrm{MeV}\\ &= m_{\pi^+}c^2 + 1.3\,\mathrm{MeV}\end{aligned}$$

So

$$\begin{aligned}m_{\pi^+}c^2 &= (140.9 - 1.3)\,\mathrm{MeV}\\ &= 139.6\,\mathrm{MeV}\end{aligned}$$

hence

$$m_{\pi^+} = 139.6\,\mathrm{MeV}/c^2$$

You will learn about π^+, π^0 and several other new particles in Section 4. The important thing now is to be able to relate changes in mass to changes in kinetic energy (Objective 2).

SAQ 2 When two hydrogen atoms collide, it sometimes happens that *one* of them is ionized, to produce a proton and an electron, whilst the other remains unchanged. In such a process, the total kinetic energy decreases by 13.6 eV. Which one of the following statements is true?

(a) The mass of a hydrogen atom exceeds the sum of the masses of an electron and a proton by 13.6 eV/c^2.

(b) The mass of a hydrogen atom is equal to the sum of the masses of an electron and a proton.

(c) The mass of a hydrogen atom is less than the sum of the masses of an electron and a proton by 13.6 eV/c^2.

3.3 Moving clocks run slow

The third effect predicted by Einstein and subsequently confirmed by experiments is perhaps the strangest of all. According to Einstein:

moving clocks run slow; the faster they move, the slower they run.

moving clocks run slow

Like the increase of inertia with speed, this effect is very small at all but the highest speeds. But it has been confirmed by flying very accurate clocks in fast aeroplanes.

It applies to *all* clocks, however they are made, and the best way to appreciate why it leads to important consequences for physicists studying high energy particles is to consider how time can be measured using the decays of particles.

decays of particles

Suppose we use the decays of radioactive nuclei to measure the passage of time, as is done in dating biblical documents (Units 10 and 11) and rocks (Unit 26). If we have nuclei whose half-life is one year, then half of them will remain after one year, a quarter after two years and so on. By measuring the radioactivity, we can determine the number of nuclei left and hence work out the time that has passed. But suppose we could put a sample in a rocket and send it off at very high speed. If the rocket returned after one year, as measured by a 'radioactive clock' left at home, how many nuclei would have decayed on the journey? According to Einstein *less than* half the nuclei would decay on the journey, because the moving clock would run *slow*. The journey would take less than one year, according to the moving nuclei, so more than half of them would remain at the end of the journey.

The consequence of the effect predicted by Einstein is that:

the rate of decay of unstable particles depends on their speed;

the faster they move, the longer they live.

We cannot yet make rockets that travel at speeds comparable to the speed of light, but unstable particles of high speed are produced in high energy physics laboratories. The dramatic effect of speed on their rate of decay has been confirmed in experiments on particles called muons, which you will meet in Section 4.3.

Now check that you understand the consequences for unstable particles of the fact that moving clocks run slow (Objective 3).

SAQ 3 The half-life of the radioactive isotope $^{90}_{38}$Sr is 30 years. That means that if you buried 32 grams of it in the year 2000, your descendants could only dig up 1 gram in the year 2150, which is 5 half-lives later. But a physicist argues as follows:

> According to Einstein, a clock moving at a speed $v = 0.6c$ only runs at 80 per cent of the rate of a clock at rest. So if I could put 32 grams of $^{90}_{38}$Sr on a rocket and send it off on a round trip at that speed, starting in the year 2000 and returning in the year 2150, then my descendants would find *more* than 1 gram left, because moving clocks run slow!

(a) How long would the trip take according to the moving radioactive clock?

(b) How many grams of $^{90}_{38}$Sr would the phycisist's descendants receive?

3.4 Summary: three new effects

The best way to remember these new effects predicted by Einstein is to remember the titles of the last three Sections.

Inertia increases with speed. This means that particles get harder and harder to accelerate at higher and higher speeds. There is no possible way to accelerate a particle to the speed of light. But electrons in the Stanford linear accelerator get *very* close to it—as do the protons in the accelerator at Geneva, which figures in TV programme 31.

Mass is not conserved. An increase in mass is always accompanied by a decrease in kinetic energy (and vice versa). The 'exchange rate' is given by $E = mc^2$. A dramatic example is the creation of new particles, using the kinetic energy available from other high energy particles.

Moving clocks run slow. This applies to all clocks: the faster they move, the slower they run. The most dramatic example is the decay of unstable particles at high speeds: the faster they move, the longer they live.

4 More particles

After the discovery of the neutron, in 1932, it seemed that physicists had succeeded in identifying the fundamental particles of matter. The answer to the question 'What is matter made of?' was the answer given in Units 10, 11 and 30: *protons*, *neutrons*, and *electrons*. Protons and neutrons are the constituents of nuclei, and they are bound together by the strong nuclear force, which extends over a very short range. Atoms are made of nuclei and electrons, bound together by weaker electromagnetic forces of longer range. Molecules are made of atoms, bound together by electromagnetic forces, according to the way they share electrons.

> There is another particle that plays a very important role in atomic processes. What is it? Would you say that it is one of the 'building blocks' of matter?

You should not forget the *photons*, which are emitted and absorbed by atoms. You know from Units 9 and 29 that photons have as much right to be called 'particles' as do electrons. They carry energy and momentum, just as electrons do, and the wave-like properties of a beam of light are also exhibited by a beam of electrons. But we do not picture atoms as containing photons. Instead, we say that a photon is *created* when an atom changes its structure and loses energy. So you can see that the search for fundamental particles is not just concerned with deciding what matter is made of; we also need to consider particles, like photons, which are created in atomic and subatomic processes.

creation of particles

In Section 4 you will learn about several new particles that are created in nuclear decays or in the collisions of particles at high energy. These discoveries were made in the period 1930–1955 and they provided the main incentive for building particle accelerators in the 1950s, to see what other sorts of particle might be found.

> **Study comment** It is not necessary to remember all the details of the particles mentioned in Section 4. The Summary Section 4.5 will tell you which are the important features that need remembering.

4.1 The positron

The first new arrival has already been mentioned in Unit 30. Positrons are particles with the same mass as electrons, but with *positive* charge. They are created in the β^+-decays of radioactive nuclei that contain too many protons to be stable. An example is the decay:

$$^{11}_{6}\mathrm{C} \longrightarrow {}^{11}_{5}\mathrm{B} + \mathrm{e}^+ \qquad (\beta^+\text{-decay})$$

Note that we say that positrons are *created* in β^+-decay. Nuclear physicists do not picture $^{11}_{6}\mathrm{C}$ nuclei as containing positrons, any more than atomic physicists picture hydrogen atoms as containing photons. Similarly, we say that electrons are *created* in β^--decays such as:

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^- \qquad (\beta^-\text{-decay})$$

You may wonder what happens to a positron after it has been created in β^+-decay. The answer involves the most spectacular example of the conversion of mass into kinetic energy. A positron passing through matter will sooner or later encounter an electron. When this happens, both the positron and the electron disappear, producing two photons. The process is called *annihilation* and we can write it in symbols as follows:

annihilation

$$\mathrm{e}^+ + \mathrm{e}^- \longrightarrow \gamma + \gamma$$

where the symbol γ represents a photon.

The entire mass of the positron and the electron is converted into the kinetic energy of the photons! Indeed, it is very easy to work out the energies of photons produced by the annihilation of positrons and electrons at rest, given the electron mass:

$$m_e = 0.511\,\mathrm{MeV}/c^2$$

ITQ 3 What is the energy (in MeV) of one of the two photons created by the annihilation of an electron and positron at rest? How does this compare with the energy of a photon of visible light (about 2 eV)?

The photons produced when positrons encounter electrons have energies more than 10^5 times greater than the photons from the hydrogen atoms which you studied at Summer School. So you can see that positrons produced in β^+-decay come to a very violent end!

4.2 The neutrino

Electrons and positrons are not the only particles produced in β-decay. There is a neutral particle, called the *neutrino*, which is produced with an electron in β^--decay or with a positron in β^+-decay*. Until the 1950s the evidence for the existence of neutrinos was indirect. It came from studying the energies of electrons and positrons in β-decay. By way of example, let us consider the β^--decay of $^{14}_{6}\mathrm{C}$, which is used in radioactive dating.

In this decay an electron and a neutrino are produced:

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^- + \nu + 0.16\,\mathrm{MeV}$$

neutrino ν

The neutrino is represented by the symbol ν, which is the Greek letter 'nu'. There is a decrease in mass of $0.16\,\mathrm{MeV}/c^2$ and hence 0.16 MeV of kinetic energy is liberated. This kinetic energy is *shared* between the electron and the neutrino: in some decays the electron gets more of it than the neutrino, in other decays it gets less. That means that electrons from $^{14}_{6}\mathrm{C}$ decay have a *range* of possible energies, between 0 and 0.16 MeV. It was the discovery that electrons from β^--decay do not have a unique energy that prompted physicists, in the 1930s, to believe that another particle was produced. The problem was to explain what happened to the missing energy in a decay in which an electron was found to have an energy less than the maximum value. The explanation offered was that this energy had been carried off by another particle—the neutrino—which had mysteriously escaped observation. This was something of a milestone in the history of physics. Rather than abandon Einstein's relationship between changes in mass and changes in kinetic energy, some physicists were prepared to believe in the existence of an undetected and rather mysterious particle: the neutrino. It was not until a quarter of a century later that neutrinos from β-decay were detected directly.

So what happens to all the neutrinos produced by the β-decays that occur in radioactive rocks, in nuclear reactors, and in the Sun? In general, *nothing* happens to them. Neutrinos interact so rarely with nuclei and electrons that the vast majority of them pass through matter without losing any energy and hence without leaving any trace at all. But just once in a while, a neutrino (of sufficiently high energy) will react with a proton to produce a positron and a neutron:

$$\nu + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n} - 1.8\,\mathrm{MeV}$$

In the late 1950s, experimental physicists were eventually able to show that the neutrinos, postulated by theoretical physicists 25 years before, did exist. The best place to look for them was near a nuclear reactor, because enormous numbers are produced in the complicated sequence of β-decays that follows the fission of uranium nuclei. With about 10^{17} neutrinos passing through a tank of water *every second*, the production of a positron by a neutrino was detected only every two minutes. It has been estimated that you would need to surround a nuclear reactor with water for a distance of 10^{19} m to recover an appreciable proportion of the energy that is carried away from the reactor by neutrinos. This distance is much further than the nearest star, so you can see that there is no hope of catching more than a tiny fraction of the neutrinos produced in β-decay.

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* In Section 4.1 of this Unit and in Section 6.3 of Unit 30 we omitted the neutrino in the formula for β-decay, in the interest of simplicity.

Neutrinos are also produced in the fusion processes that occur in the Sun. The energy they carry is a few per cent of the energy radiated from the Sun. But neutrinos do not help to keep you warm. The vast majority of neutrinos pass right through you and the Earth, without leaving a trace, and continue on their journey to distant regions of the Universe.

4.3 Pions and muons

cosmic rays

In addition to photons and neutrinos from the Sun, the Earth receives cosmic rays from more distant parts of the Universe. This cosmic radiation consists of protons, nuclei and electrons, some of which have extremely high energy. A *single* cosmic ray proton can sometimes have as much kinetic energy as a *cricket ball* from a fast bowler: an energy of 10^{21} eV, or 160 J, which is an amazingly large energy for a single proton. (The highest energy protons produced by particle accelerators have energies of 5×10^{11} eV, which is a puny amount on this cosmic scale.) The origin of cosmic rays is still something of a mystery, but they must come from extremely violent processes. A possible source could be supernovae—the explosions of stars which are observed about once every 30 years in our galaxy.

pions
, π^0 and π^-

In the period 1937–1950, cosmic rays played an important role in revealing the existence of particles called *pions* and *muons*. When a cosmic ray particle collides with an oxygen or nitrogen nucleus in the upper atmosphere, new particles are created. Most copiously produced are pions, which come in three varieties: the positively charged π^+ (pi plus), the negatively charged π^- (pi minus) and the neutral π^0 (pi zero).

You met the neutral pion in Section 3.2, where you saw how its mass (135 MeV/c^2) could be calculated from the change in kinetic energy when it is created in the collision of protons. It decays very quickly into two photons:

$$\pi^0 \longrightarrow \gamma + \gamma$$

otographic
emulsion

and its existence has only been inferred indirectly by studying the photons produced. But *charged* pions (π^+ and π^-), produced by cosmic rays, were first detected by the tracks they left in detectors containing photographic emulsion. This emulsion is similar to (but more sensitive than) the material from which ordinary film is made. A *charged* particle, such as π^+ or π^-, loses energy by ionizing atoms when it passes through matter. Some of this energy is stored in the silver bromide of the photographic emulsion, which when developed reveals a tell-tale track of silver grains along the path taken by the particle. In Figure 2 you can see a sequence of three tracks made by particles in such an emulsion. The track from A to B was made by a π^-, produced by cosmic rays. The track from C to D was made by an electron. But what happened between B and C? At B, the π^- decayed to produce a *muon*. Muons come in two varieties: the negatively charged μ^- (mu minus) and the positively charged μ^+ (mu plus). At B, the π^- decayed into a μ^- and a neutrino:

muons
$^-$ and μ^+

$$\pi^- \longrightarrow \mu^- + \nu$$

The neutrino escaped observation. Because neutrinos are neutral, they do not leave tracks in the emulsion, they pass right through it without losing any energy. But the μ^- left a clear track from B to C. At C the μ^- itself decayed, producing an electron and *two* neutrinos:

$$\mu^- \longrightarrow e^- + \nu + \nu$$

In giving this description of pion and muon decay we have jumped a lot of history. You cannot, for example, discover that two neutrinos are produced in μ^--decay merely by looking at Figure 2. The purpose of showing this photograph is to let you see that some of these new particles *do* leave detectable tracks. But we do not have time to explain just how the information from cosmic ray studies was unravelled to reveal the properties and decays of pions and muons.

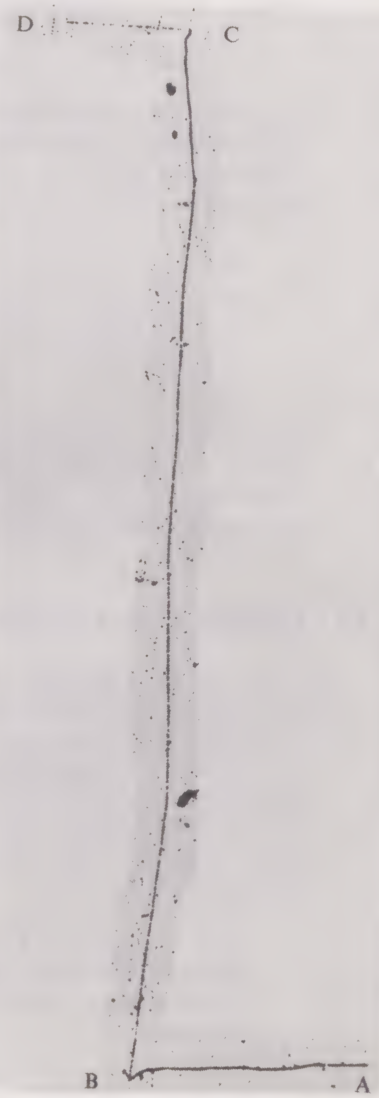

FIGURE 2 Tracks left by a pion, muon and electron in emulsion.

What about the positively charged pions, π^+? They decay into μ^+ particles, which in turn decay into positrons:

$$\pi^+ \longrightarrow \mu^+ + \nu$$

$$\mu^+ \longrightarrow e^+ + \nu + \nu$$

So, apart from the difference in sign of the charges of the particles, the sequence of events is much the same as in π^--decay.

The pions produced by cosmic rays and the muons produced in pion decay often have very large kinetic energies, corresponding to speeds very close to the speed of light. You should remember from Section 3.3 that Einstein predicted a dramatic effect at such speeds: moving clocks run slow and hence high speed particles live longer than particles at rest. Muon decay offers an impressive confirmation of this prediction. It has been found that muons *at rest* decay with a half-life of 1.5×10^{-6} s. So how far can muons travel down through the Earth's atmosphere before they decay? Suppose we start with N muons, travelling with a speed $v = 0.995\,c$, at a height of 4.5 km above sea-level. According to a clock on Earth it would take a time:

$$\frac{4.5 \times 10^3\,\text{m}}{3 \times 10^8\,\text{m}\,\text{s}^{-1}} = 1.5 \times 10^{-5}\,\text{s}$$

for a muon to get down to sea-level, travelling at a speed of almost c. This is 10 times the half-life of a muon at rest. So, *if* muons decayed at the same rate at high speeds as they do at rest, we would expect to find only a very small number:

$$N \times (\tfrac{1}{2})^{10} = 0.001\,N$$

at sea-level. But, in fact, Einstein's theory says that a clock travelling at 99.5 per cent of the speed of light should run 10 times more slowly than one at rest. That means that the journey down to sea-level only takes *one* half-life of the muons with speed $v = 0.995\,c$, so half of them will make it without decaying.*

> **ITQ 4** Physicist A knows that 'moving clocks run slow' and expects to find 5000 muons with speed $v = 0.995\,c$ at sea-level. He turns out to be right. But physicist B has forgotten about Einstein's theory. How many will he expect, assuming that he agrees with A about the number at a height of 4.5 km?

You can see that many more muons (in this example 500 times as many) will be detected at sea-level than would be expected if you did not know that 'moving clocks run slow'. Experiments have been performed to measure the flux of muons of various speeds at different heights and the results confirm Einstein's theory.

4.4 Hadrons, leptons and the photon

In the last three Sections, the number of types of particle has grown rather alarmingly. To your familiar friends—the proton, neutron, electron and photon—several new-comers have been added. But this is only the beginning of the story! There are yet more types of particle produced by cosmic rays and in high energy physics laboratories, which you will learn about in Section 5. But before mentioning any more particles, it will be useful if we divide the ones you have already met into groups. Then, whenever a new particle is introduced, we shall be able to say which group it belongs to.

> **ITQ 5** In Section 4 we have already mentioned eleven particles (excluding molecules, atoms, and nuclei more complicated than the proton). Make a list of these eleven particles (referring back to Sections 4.1–4.3, if necessary).

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* The dependence of half-life on speed, which you do *not* need to remember, is given by:

$$\frac{\text{number of half-lives of muons of speed } v}{\text{number of half-lives of muons at rest}} = \sqrt{1 - v^2/c^2}$$

(a) Which *two* particles are the constituents of nuclei?

(b) Which *three* particles are the constituents of atoms?

(c) Which *three* particles are created in β^-- or β^+-decay?

(d) Which particle is created when an electron jumps from an excited state of a hydrogen atom down to the ground state?

(e) Which *five* particles were discovered in cosmic ray studies?

(f) Which *three* particles are created in the decays of charged pions, mentioned in Section 4.3?

(g) Which *four* particles are neutral (i.e. have zero electric charge)?

As indicated by ITQ 5, there are many different ways of classifying the eleven particles of Table 1. But the most useful way of dividing them into groups turns out to be the one shown in the Table, where they have been divided into three groups: *hadrons* (which include neutrons, protons and pions), *leptons* (which include muons, electrons, positrons and neutrinos), and finally the *photon*, in a class of its own.

These three groups will now be discussed in turn, so that you can get an idea of the common characteristics of the particles in a group, and the ways in which they differ from particles in another group.

TABLE 1 Hadrons, leptons and the photon

	negative charge	neutral	positive charge	
HADRONS		n	p	neutron and proton
	π^-	π^0	π^+	pions
LEPTONS	μ^-		μ^+	muons
	e^-		e^+	electron and positron
		ν		neutrino
PHOTON		γ		photon

4.4.1 Hadrons and strong interactions

hadron

strong interaction

The first group of particles contains the proton and neutron, from which nuclei are made, and the pions, which are created in the collisions of protons and neutrons. These particles are called *hadrons*. The word hadron is derived from a Greek word meaning 'bulky', and it indicates that these particles have larger masses than the lighter leptons. But another and more important distinguishing characteristic of hadrons is that they interact *strongly* with each other. You already know that there is a strong force which binds protons and neutrons together in nuclei. That is just one aspect of what is meant by saying that hadrons have 'strong interactions'. Another expression of the strength of the interactions between hadrons is the rate at which pions are produced in collisions between protons and neutrons, in reactions* such as:

$$\left.\begin{array}{l} \mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^0 \\ \mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+ \\ \mathrm{p} + \mathrm{n} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^- \\ \mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^+ + \pi^- + \pi^0 \end{array}\right\} \text{(strong interactions)}$$

Note that several pions can be created if there is sufficient kinetic energy available: an impressive example of $E = mc^2$.

---

* Do *not* attempt to remember the reactions and decays that are mentioned in Section 4.4. They are included to illustrate the general ideas, which are summarized in Section 4.5. You will not, for example, be expected to know all the things that can happen when two protons collide.

Such reactions occur very frequently when a beam of high energy protons passes through matter, whereas you know that neutrinos interact with other particles only very rarely. The pions produced in these reactions also interact strongly with protons and neutrons. For example, charged pions passing through matter can produce neutral pions:

$$\left.\begin{aligned}\pi^- + p &\longrightarrow n + \pi^0\\ \pi^+ + n &\longrightarrow p + \pi^0\end{aligned}\right\} \quad \text{(strong interactions)}$$

or, if the original pions have sufficient energy, several new pions can be produced:

$$\left.\begin{aligned}\pi^- + p &\longrightarrow n + \pi^+ + \pi^-\\ \pi^+ + n &\longrightarrow p + \pi^+ + \pi^- + \pi^0\end{aligned}\right\} \quad \text{(strong interactions)}$$

All these processes are examples of strong interactions between hadrons. The important thing to remember is that *hadrons interact strongly with one another to produce other hadrons*. We shall say more about hadrons in Sections 5 and 6.

4.4.2 Leptons and their interactions

lepton

The second group of particles contains the electron, positron and neutrino, which are created in β-decay, and the muons, which are created in the decays of charged pions. These particles are called *leptons*. The word lepton is derived from a Greek word for a small coin and it indicates that these particles have smaller masses than the heavier hadrons. But another and more important distinguishing characteristic of leptons is that they are *not* produced directly by strong interactions, which occur when hadrons collide. Instead, they come from some of the *decays* of nuclei, hadrons, or leptons. You have already met several examples of decays in which leptons are created.

ITQ 6 In each of the following decays leptons are created:

(i) $\pi^+ \longrightarrow \mu^+ + \nu$

(ii) $\pi^- \longrightarrow \mu^- + \nu$

(iii) $\mu^+ \longrightarrow e^+ + \nu + \nu$

(iv) $\mu^- \longrightarrow e^- + \nu + \nu$

(v) ${}^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + e^- + \nu$

(vi) ${}^{11}_{6}\text{C} \longrightarrow {}^{11}_{5}\text{B} + e^+ + \nu$

(a) Identify *all* the leptons involved, by ringing them with circles. What are their names?

(b) In two of the decays, a hadron disappears, leaving only leptons. Which are these two decays?

(c) In two of the decays, a lepton disappears, creating new leptons. Which are these two decays?

(d) What is the name given to decays such as (v) and (vi)?

You know that *hadrons* have *strong* interactions with other hadrons, in which yet more hadrons can be produced. For example:

$$p + p \longrightarrow p + n + \pi^+ \qquad \text{(\textit{strong} interaction)}$$

But what about *leptons*? They have *no* strong interactions, so what interactions *do* they have? Well there are *two* kinds of interaction of leptons, called *electromagnetic** interactions and *weak* interactions. We shall illustrate them in turn, with a couple of examples each.

First of all, you know that all the leptons, *except the neutrino*, are charged. So when a *charged* lepton (e^-, e^+, μ^- or μ^+) gets near to an electron or proton in matter, it will be affected by an electric force. By way of an example, consider a beam of electrons passing through a gas that contains some hydrogen that has been ionized to produce free protons and electrons. An electron may be deflected out of the beam if it has a close encounter with a proton. This is an example of an *electromagnetic* interaction. The equation is very simple:

---

* The word electromagnetic is chosen to encompass the effects of the *electric* forces between *stationary* charged particles and the *magnetic* forces between *moving* charged particles.

electromagnetic interaction

$$e^- + p \longrightarrow e^- + p \quad (\textit{electromagnetic}\text{ interaction})$$

No new particles are created in this interaction and the total kinetic energy of the two particles remains the same because there is no change in mass.

It is tempting to try to depict such an interaction by the diagram of Figure 3a. But it is also very dangerous! The diagram appears to contain the following information:

> An electron with initial kinetic energy E is deflected through an angle of 60° by a close encounter with a proton at rest. The distance of closest approach is given by the equation:
>
> $$d = \left(\frac{7.2\,\text{eV}}{E}\right) \times 10^{-10}\,\text{m}$$

This is the sort of statement a physicist might have made *before* the advent of quantum theory. Indeed, the relationship between the distance d and the energy E is the one which follows* from Coulomb's law of electrostatic force (Unit 8) and Newton's second law of motion (Unit 3). *But it completely ignores Heisenberg's uncertainty relation* (Unit 29). Remember that this uncertainty relation says that if you have very accurate information about where the proton is (small uncertainty in position), you *cannot* be sure of how fast it is moving (large uncertainty in momentum) and, in particular, you cannot claim it is at rest. Conversely, if you know that the proton has a small momentum, you cannot be sure of its position. The same uncertainty relation applies to the electron, so it makes no sense to represent the process by Figure 3a *unless* the uncertainties in position and momentum can be made much smaller than the distance d and the momentum of the electron respectively. It turns out that if d is too small (or, equivalently, if E is too large), the uncertainties become comparable to the quantities that are specified in the Figure, and it cannot provide a satisfactory description of the interaction.

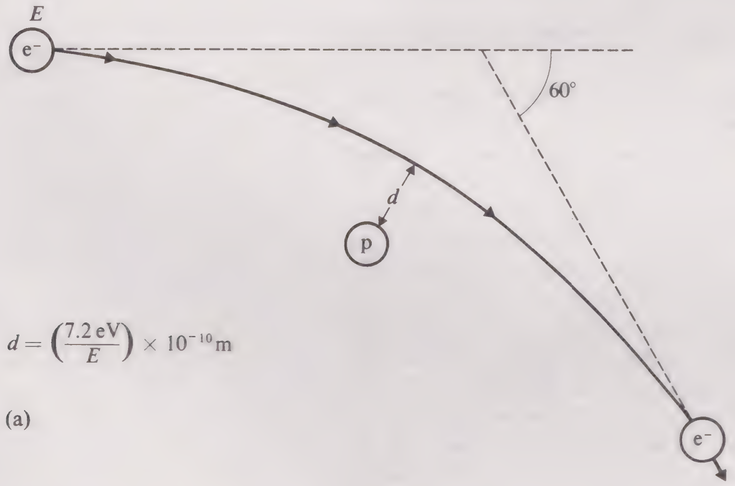
E
e⁻
60°
d
p
$d = \left(\frac{7.2\,\text{eV}}{E}\right) \times 10^{-10}\,\text{m}$
(a)
e⁻

FIGURE 3 (a) Is such a description permitted?

It is not difficult to find an energy E for which the picture of Figure 3a breaks down. If E is of the order of *a few electronvolts*, the formula claims that d is of the order of the size of a hydrogen atom (10^{-10} m), and you know that an electron and a proton in a hydrogen atom *cannot* be pictured in the way we picture everyday billiard balls or bodies in the solar system.

In conclusion, the electromagnetic interaction of an electron and a proton, involving a large deflection, cannot be described by such a picture if the kinetic energy of the electron is of the order of an electronvolt or larger.

High energy physicists study the electromagnetic interactions of electrons with energies of 10^8–10^{10}electronvolts. That is why you will not find any more Figures like Figure 3a in this Unit! Look instead at Figure 3b, which gives a *less* dangerous description because it does *not* attempt to represent any details of the interactions within the target. It merely shows an electron entering a hydrogen target from a source and leaving it, having been deflected by 60°, after which it is detected.

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* The mathematics involved in such a calculation is beyond the level that we use in this Course. It is the same mathematics as is needed to calculate the path of a comet in the solar system: differential and integral calculus.

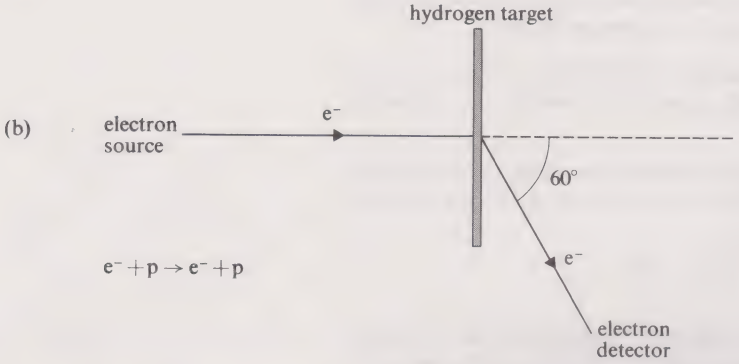


FIGURE 3 (b) A possible outcome.

That (in very crude terms) is one way a high energy physicist might detect the simple electromagnetic interaction:

$$e^- + p \longrightarrow e^- + p \qquad (\textit{electromagnetic}\text{ interaction})$$

He calls it an electromagnetic interaction because he believes that it is the same sort of interaction as one that can be described by Figure 3a and by Coulomb's law, at *low* energies. But at *high* energies he is not allowed by Heisenberg to describe the interaction by Figure 3a.

This discussion may make the next example of an electromagnetic interaction less surprising. Suppose the high energy physicist has *two* detectors, as in Figure 3c. And suppose he detects an electron *and* a positively charged pion π^+. What could have happened? What sort of interaction will he call it? A possible interaction is:

$$e^- + p \longrightarrow e^- + n + \pi^+ - 140.9\,\text{MeV} \qquad (\textit{electromagnetic}\text{ interaction})$$

In fact, careful measurements of the momentum and energy of the electron and pion could be made to test this hypothesis, using the law of conservation of momentum (Unit 29) and Einstein's equation $E = mc^2$ (Section 4.2). You need not bother about how this is done; let's just assume that it has been checked. The question at issue is why this interaction is called 'electromagnetic'. The answer is the same answer as that given for the experiment of Figure 3b. The physicist believes that the same laws of electromagnetism that are expressed by Coulomb's law at *low* energy, and that govern the interaction of Figure 3b at *any* energy, also govern the interaction of Figure 3c when the energy is *high* enough to allow the creation of a pion. But if you ask him to draw a picture like Figure 3a to describe the interaction of Figure 3c, he will not be able to oblige. Heisenberg says that pictures like Figure 3a are *wrong* at high energies, and Einstein says that the creation of 140.9 MeV/c^2 of extra mass can occur *only* at high energies. So, between them, he is in a cleft stick! The best he can hope to do is to find laws of electromagnetism that satisfy both the requirements of quantum theory and the

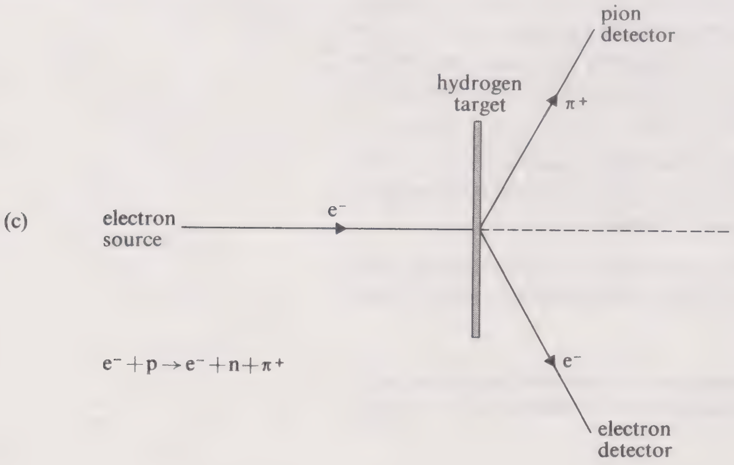


FIGURE 3 (c) Another possible outcome.

requirements of the special theory of relativity, and that are equivalent to Coulomb's law (and the laws of magnetic force) at low energies, when neither quantum nor relativistic effects are important. Much progress has been made along these lines in the last 30 years but, unfortunately, the equations that express the laws of what is called 'quantum electrodynamics' are far beyond the level of this Course. That means that we will only be able to *tell* you what happens in the processes of high energy physics rather than describe them pictorially or by quantum equations. (But, by way of compensation, there is much we *can* say about the 'search for fundamental particles'.)

weak interaction

So now you have seen examples of the *electromagnetic* interactions of *charged* leptons, like the electron, what about the other sort of interactions, called *weak* interactions? An example of such an interaction was given in Section 4.2 on the neutrino:

$$\nu + p \longrightarrow e^+ + n \qquad (\textit{weak}\text{ interaction})$$

Neutrinos are uncharged and have *no* electromagnetic interactions. They do not have strong interactions either, otherwise they would have been classified as hadrons. That is why a new adjective is needed to describe the interactions of neutrinos: they are called *weak*. Remember that most neutrinos from the Sun get right through the Earth without interacting at all. That's how weak their interactions are! But neutrinos of sufficient energy can produce other particles in their weak interactions, even though they do so rarely. For example pions can be produced:

$$\nu + p \longrightarrow e^+ + p + \pi^- \qquad (\textit{weak}\text{ interaction})$$

Charged leptons (e.g. e^+) have weak interactions, in which neutrinos can be produced, but these occur less often than electromagnetic interactions*.

An example is: $$e^+ + n \longrightarrow \nu + p \qquad (\textit{weak}\text{ interaction})$$

That completes the discussion of *leptons*. The important things to remember are that leptons:

(a) have *no* strong interactions;
(b) are produced in some of the decays of nuclei, hadrons or leptons;
(c) have electromagnetic interactions, if they are charged;
(d) have weak interactions (the only interactions of neutrinos).

Leptons will not figure much in Sections 5–8, which are concerned with hadrons. But they have an important role to play in Section 9.

4.4.3 The photon and electromagnetic interactions

Finally, we have reserved a special category for the photon. The existence of the photon is intimately connected with the existence of electromagnetic forces acting between charged particles. Photons are the quanta of light. And light (as you saw in Units 9 and 29) also exhibits behaviour, such as diffraction, that can be described in terms of an electromagnetic wave. It seems reasonable then that if there were no electromagnetic forces operating between charged particles, there would be no such thing as light and hence no photons. It is believed that interactions such as

$$\left.\begin{aligned} e^- + p &\longrightarrow e^- + p \\ e^- + p &\longrightarrow e^- + n + \pi^+ \end{aligned}\right\} \qquad (\textit{electromagnetic}\text{ interactions})$$

depend crucially on the existence of the photon, even though photons are not created in these processes. Indeed, the photon has proved to be the key concept in understanding electromagnetic interactions at high energy, where the requirements of quantum theory and relativity forbid one from talking in terms of forces. Although photons are not always created in electromagnetic interactions, they always have a role to play in the quantum theory of such interactions. You have, however, met an example of an electromagnetic interaction in which photons *are* created: the annihilation of positrons and electrons mentioned in Section 4.1:

$$e^+ + e^- \longrightarrow \gamma + \gamma \qquad (\textit{electromagnetic}\text{ interaction})$$

---

* Despite the difference in strength between electromagnetic and weak interactions, much progress has been recently made in unifying them into a *single* theory of lepton interactions. But such developments lie outside the scope of this Unit.

It is believed that there may be other types of particle, associated with other types of force or interaction. Physicists have not yet succeeded in detecting the particles that are believed to be associated with the gravitational force, or with the strong interactions of hadrons, or with the weak interactions of neutrinos, but they live in hope that one day such particles will be found and have already coined names for them (such as 'gravitons', 'gluons', and 'weak bosons'). But such speculations lie somewhat outside the development of the rest of this Unit, which is concerned with the story of *hadrons* and why they are *not* believed to be fundamental particles.

The important thing to remember is that *photons are the particles associated with electromagnetic forces.*

4.5 Summary: the story so far

Three groups of particles have been discussed:

(a) *Hadrons* include the proton and neutron (p and n) and the pions (π^+, π^0 and π^-). Hadrons are particles that interact strongly with one another to produce other hadrons. For example:

$$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+ \qquad (\textit{strong}\text{ interaction})$$

(b) *Leptons* include the electron, positron and neutrino (e^-, e^+ and ν), which are all created in β-decay, and muons (μ^- and μ^+), which are created in pion decay.

All but the neutrino have electromagnetic interactions (which are not as strong as strong interactions). For example:

$$e^- + \mathrm{p} \longrightarrow e^- + \mathrm{n} + \pi^+ \qquad (\textit{electromagnetic}\text{ interaction})$$

But the interactions of neutrinos are much weaker. For example:

$$\nu + \mathrm{p} \longrightarrow e^+ + \mathrm{n} \qquad (\textit{weak}\text{ interaction})$$

Leptons have *no* strong interactions and are *not* produced directly in the strong interactions of hadrons. They are created in some of the decays of nuclei, hadrons or leptons. For example:

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + e^- + \nu$$

$$\pi^+ \longrightarrow \mu^+ + \nu$$

$$\mu^+ \longrightarrow e^+ + \nu + \nu$$

(c) The *photon* is a special particle that is associated with the existence of electromagnetic forces between charged particles.

Three sorts of interaction have been discussed. In order of strength they are:

(a) the *strong* interactions of hadrons;

(b) the *electromagnetic* interactions of charged particles;

(c) the *weak* interactions of neutrinos.

Three effects predicted by Einstein have been discussed, with examples of their confirmation in the studies of high energy particles:

(a) *Inertia increases with speed.* A consequence is that no particle can travel faster than light in a vacuum. This is confirmed, for electrons of the highest energy available, at the Stanford linear accelerator (and at every other accelerator laboratory).

(b) *Mass is not conserved.* In particular, dramatic changes in mass can occur, provided there are compensating changes in kinetic energy, according to the equation $E = mc^2$. Most spectacular are the annihilation of a positron and an electron:

$$e^+ + e^- \longrightarrow \gamma + \gamma$$

and the creation of new particles, such as pions:

$$\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+$$

(c) *Moving clocks run slow* and hence fast particles live longer. For example, far fewer muons would be found at sea-level if this were not the case.

Now check that you can distinguish between hadrons and leptons (Objective 4).

SAQ 4 (a) How many hadrons are there in a hydrogen molecule?

(b) Does the number of hadrons change in β-decay?

(c) How many leptons are produced in one β-decay?

(d) How many leptons are there in a water molecule?

(e) Does every water molecule contain the same number of hadrons?

Now check that you can distinguish between reactions of different strength (Objective 5).

SAQ 5 Suppose that a beam of high energy particles is produced at a physics laboratory and that it contains *protons, muons* and *neutrinos* in roughly equal proportions. When the beam collides with a target, pions can be produced in a variety of reactions which includes:

(i) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+$

(ii) $\mu^+ + \mathrm{p} \longrightarrow \mu^+ + \mathrm{n} + \pi^+$

(iii) $\nu + \mathrm{p} \longrightarrow \mu^- + \mathrm{p} + \pi^+$

Which particles (p, μ^+ or ν) will produce pions most often? Which will produce pions least often?

Now check that you can relate changes in mass to changes in kinetic energy (Objective 2).

SAQ 6 In the following reactions and decays the changes in kinetic energy have been indicated.

(i) $\mathrm{e}^+ + \mathrm{e}^- \longrightarrow \gamma + \gamma + 1.0\,\mathrm{MeV}$

(ii) $\mu^- \longrightarrow \mathrm{e}^- + \nu + \nu + 105.2\,\mathrm{MeV}$

(iii) $\mu^+ \longrightarrow \mathrm{e}^+ + \nu + \nu + 105.2\,\mathrm{MeV}$

(iv) $\pi^0 \longrightarrow \gamma + \gamma + 135.0\,\mathrm{MeV}$

(v) $\pi^- \longrightarrow \mu^- + \nu + 33.9\,\mathrm{MeV}$

(vi) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+ - 140.9\,\mathrm{MeV}$

Use this information and the masses given in the list below to complete the list of particle masses. Verify that all the hadrons are heavier than all the leptons.

	Particle	Mass/MeV/c^2
PHOTON	γ	0
LEPTONS	ν	0
	e^-	0.5
	e^+	
	μ^-	
	μ^+	
HADRONS	π^0	
	π^-	
	π^+	
	p	938.3
	n	939.6

5 Many more hadrons

Cosmic ray studies in the early 1950s revealed the existence of yet more hadrons, but it was very difficult to learn how they were produced in the atmosphere. The problem with cosmic rays is that you cannot know in advance where, or when, or with what energy they will arrive. What is needed for a systematic study of hadrons is an intense, reliable source of high energy particles, whose reactions and decays can then be analysed in controlled situations. In response to this need, scientists and technologists have produced some of the world's most remarkable machines—the particle accelerators.

particle accelerator

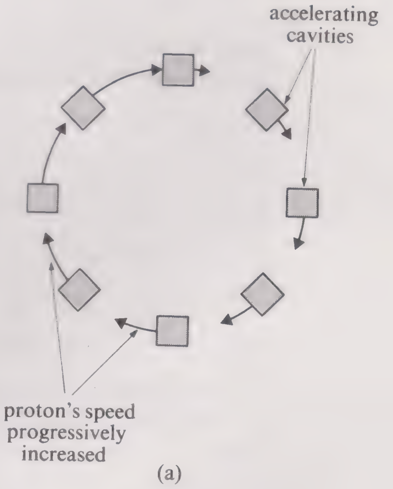
5.1 Accelerators

linear accelerator

In Section 3.1 we mentioned one type of accelerator—a *linear* accelerator. At Stanford, *electrons* are accelerated down a long evacuated tube by means of an electric field. The electrons increase their energy by about 7 MeV for every metre they travel down the tube, so that after a distance of 3 km they have an energy of 21 GeV. This is the highest energy to which electrons have yet been accelerated. The electric field is close to the maximum that can be provided by current technology, so to achieve a higher energy one would need a longer machine. The length of a linear accelerator is limited by the costs of building it and providing the power to operate it, and it is unlikely that higher energies will be achieved using linear accelerators.

synchrotron

The highest energy *protons* available at present are accelerated by a different sort of machine, called a *synchrotron*. The idea behind a proton synchrotron is very simple. A batch of protons is made to travel many times round a circle. At various points on the circle there are special devices, called cavities, which provide alternating electric fields to accelerate the protons. Because the protons travel round the circle many times, the same cavity can be used to accelerate them *many times in succession*, as illustrated in Figure 4. The oscillations of the electric fields in the cavities have to be *synchronized* with the arrival of the protons so that each time there is a gain of energy—hence the name of the machine.



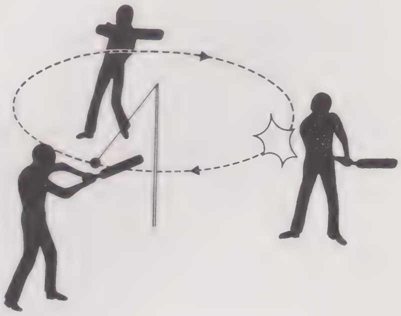


FIGURE 4 (a) In a proton synchrotron the protons are repeatedly accelerated by the same cavities.

(b) An analogy for a synchrotron.

But what makes the protons travel in a circle? You know from Unit 3 that there must be a force acting on the protons, directed towards the centre of the circle. This force is, in fact, a *magnetic* force, provided by a large number of very strong magnets placed round the circle. As the energy of the protons increases, a greater force is required to keep them moving in the same circle and the magnetic field must be constantly increased during the process of acceleration, in accordance with calculations based on the special theory of relativity. This is achieved by increasing the electric currents flowing in coils that are wound round the iron from which the magnets are made. So you can see that it takes a great deal of ingenuity to realize the simple idea expressed by Figure 4.

In the 1950s the European nations (including Britain) pooled their resources to build a proton synchrotron in Geneva at CERN (the laboratory of the European Organization for Nuclear Research). The machine was completed in 1959 and produced protons with an energy of about 30 GeV. More recently an even bigger machine has been built on the same site: CERN now has a 'super proton synchrotron' (SPS) with which energies of 400 GeV can be achieved. Large proton synchrotrons have also been built in the U.S.A. and the U.S.S.R.

From Table 2 you can see that high energies require large radii. The approximate relationship is:

$$E \approx 0.3Br$$

where E = maximum energy/GeV
B = maximum magnetic field/tesla
r = radius of machine/m

The maximum magnetic field that can be produced by iron-cored electromagnets is of the order of 1 tesla, which is why you need a radius of about 100 m to get an energy of about 30 GeV, and a radius of about 1 km to get an energy of about 300 GeV. So, just as in the case of a linear accelerator, the requirement of high

TABLE 2 Proton synchrotrons

Energy/GeV	Laboratory	Approx. date of completion	Radius/m
500	Fermilab, Illinois, U.S.A.	1973	1 000
400	CERN SPS, Geneva	1977	1 100
70	Serpukhov, U.S.S.R.	1967	235
30	Brookhaven National Laboratory, Long Island, U.S.A.	1960	129
30	CERN PS, Geneva	1959	100

energy can only be met by building a large machine. An indication of the sizes of the machines at CERN is given by the aerial photograph of Figure 5 and by the film shown in TV programme 31.

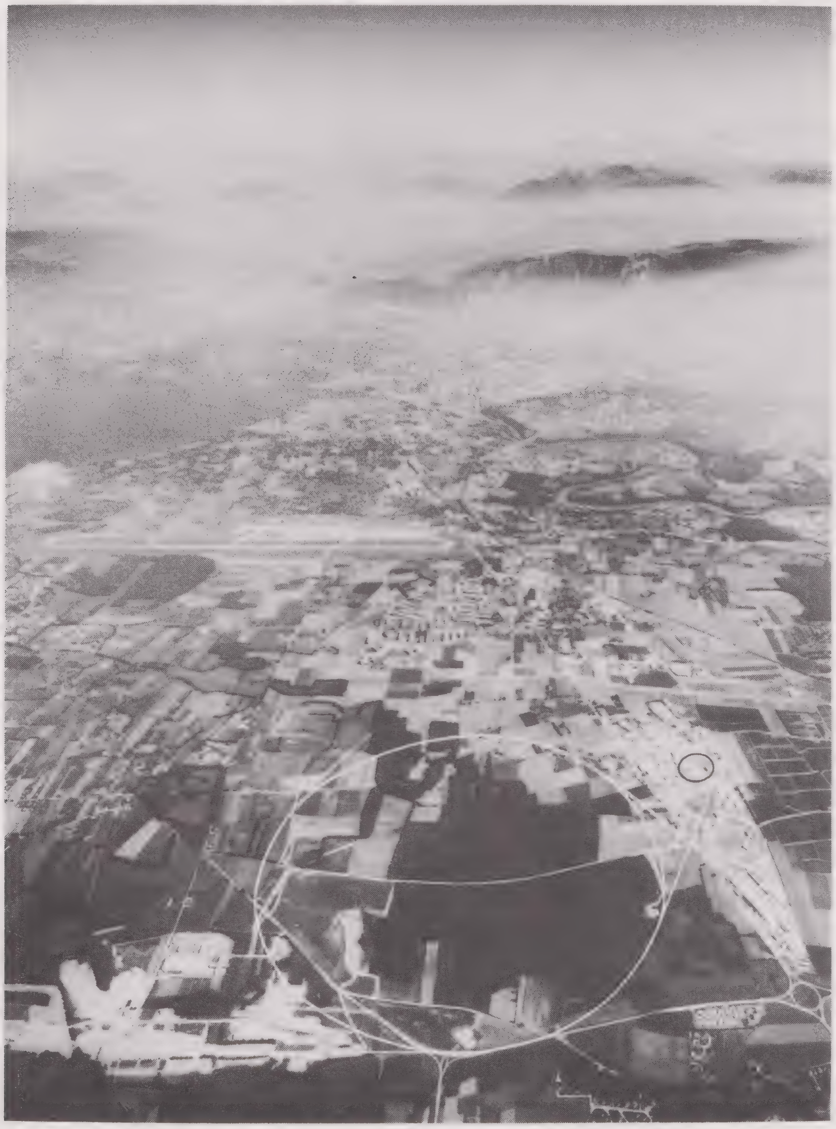


FIGURE 5 The European Organization for Nuclear Research (CERN) at Geneva. The CERN SPS is in an underground tunnel, indicated by the large circle. The CERN PS is indicated by the small black circle to the right of the SPS.

5.2 Beams

For all their size, cost and complexity, particle accelerators have a very simple job to do: to produce an intense beam (or bursts) of high energy protons or electrons. This beam is then made to collide with a target*. New hadrons are produced by the collision, in much the same manner as pions are produced by the collisions of cosmic rays with matter in the Earth's atmosphere. The job of a high energy physicist is to investigate the properties of these particles—to find out how they react with the neutrons and protons of matter and how they decay. The first step is to try to sort out the jumble of particles of different charge, mass and energy, that is produced. For example, a team of physicists might want to study what happens when pions of negative charge (π^-), with an energy of between 5 and 6 GeV, pass through hydrogen. In such an experiment they wouldn't want pions of positive charge (π^+) passing through their apparatus. Nor would they want other negative particles (such as μ^-), or even π^- particles whose energy was less than 5 GeV or more than 6 GeV. But some of these 'unwanted' particles might be of interest to another team, performing a different experiment elsewhere in the laboratory.

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* At some laboratories, the collision of one beam with another is studied. Such studies complement the ones we discuss in this Unit.

It turns out to be possible to select particles of a desired charge, mass, and range of energy, by a careful arrangement of magnetic and electric fields. The details of how this is done need not concern us here, but you should appreciate that this sorting process is a very important part of an experiment in high energy physics.

ITQ 7 Given the choice of beams of protons, or of muons, or of neutrinos, of equal energy and intensity, which would you choose for each of the following purposes?

(a) A study of pions.

(b) A study of electromagnetic interactions.

(c) A study of weak interactions.

It is one of the characteristics of the scientific method that one tries to focus attention on only a few phenomena in any given experiment. This means trying to eliminate as many extraneous effects as possible.

5.3 The bubble chamber

Suppose the technical staff at a high energy physics laboratory has provided a team of experimenters with a carefully aimed beam of π^- particles, with energies of 5–6 GeV. How can the team detect what happens when these particles pass through hydrogen? In this Section we shall describe an ingenious device, called a *bubble chamber*, with which the interactions and decays of subnuclear particles can be detected. High energy physicists have other detectors at their disposal, but we shall concentrate on the bubble chamber, because the information it gives is in a convenient visual form, which you can study for yourself in Section 5.7.

bubble chamber

In a bubble chamber, the paths of charged particles are made visible by the tracks of bubbles that the particles make when passing through a liquid that is on the point of boiling. A hydrogen bubble chamber is a vessel containing *liquefied* hydrogen, under pressure. The temperature at which the hydrogen will boil depends upon the pressure: the lower the pressure, the lower the boiling temperature. The chamber is provided with a piston that can be used to lower or raise the pressure. If the pressure is lowered and the temperature kept constant, the hydrogen will start to boil, because the boiling temperature is now lower than the temperature of the liquid. (By way of analogy suppose you had some liquid water at a temperature of 110 °C inside a pressure cooker or a car radiator. You could make this water boil by releasing the pressure*, so that the boiling temperature fell from above 110 °C to the value at atmospheric pressure, 100 °C). Now when hydrogen boils, bubbles of hydrogen gas are formed in the liquid. But where will the bubbles form? In order for a bubble to grow, it must have some sort of 'centre' from which to start. Usually this consists of some irregularity in the containing vessel—a sharp corner where the sides join or perhaps an imperfection on the surface. (Check this next time you are boiling an egg.) But *ionized* atoms can also provide suitable centres for bubble growth. When a charged particle, such as a π^-, passes through the liquid hydrogen its electric charge interacts with that of the electrons belonging to the atoms of hydrogen lying in its path, and some of these atoms are ionized. Thus, if a charged particle happens to be passing through the bubble chamber at the moment when the pressure is lowered, its track will be marked by a trail of bubbles that can be illuminated and photographed from different angles. And if the particle interacts with one of the protons of hydrogen to produce new charged particles, or if charged particles are produced in decay processes, they too will leave tell-tale tracks that can be recorded on film that the physicist can develop and study later. Such bubble-chamber photographs were shown in TV29, to give evidence for the particle-like properties of electrons.

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* Do *not* attempt such an experiment!

The sequence of events in the operation of a bubble chamber is summarized in Figure 6.

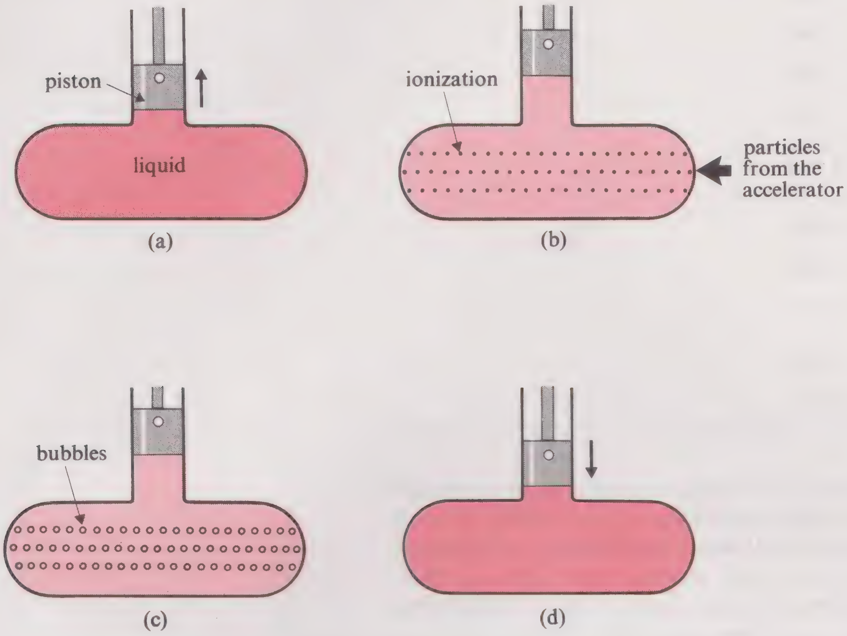

FIGURE 6 The sequence of operations in a bubble chamber. (a) The piston is raised, so releasing the pressure on the liquid. (b) Particles from the accelerator pass into the chamber and ions are formed. (c) In a few milliseconds the bubbles grow to a visible size. Stereophotographs are now taken by flashing the lights. (d) The piston is lowered to its original position, so restoring the initial pressure. The bubbles collapse.

5.4 Strange hadrons

Bubble chambers are usually placed in strong magnetic fields, which deflect charged particles, causing the tracks to be curved. (You will see examples in Sections 5.7.) When a π^- particle interacts with a proton, to produce new charged hadrons, it is often possible to determine the mass, charge and energy of these new hadrons from detailed measurements of the curvature of their tracks and the number of bubbles per unit length produced along the tracks. It is even possible to extract information about *neutral* particles produced in reactions or decays, by using the laws of conservation of momentum and energy. (Neutral particles, such as the photon and neutron, do not leave tracks, because they do not ionize the hydrogen, but it may be possible to work out which way they went, and what their mass and energy were, from determinations of the momenta, masses and energies of the charged particles, which *do* leave tracks.)

We are not concerned in this Unit with how quantitative measurements are made, using bubble-chamber photographs. What is important is that such studies reveal the existence of *new hadrons*—particles that are produced in the collisions of the hadrons you already know (p, n, π^+, π^0, π^-) and that can be distinguished from the 'old' hadrons by their masses, interactions and decays. For historical reasons, these new hadrons were called *strange* hadrons (and in Section 5.6 we shall

strange hadron

describe a new rule which enabled theorists to *quantify* just how 'strange' they are). In Table 3 we have listed some of the strange hadrons discovered in the 1950s.

TABLE 3 Strange hadrons

Symbol	Name	M Mass/MeV/c^2	Q Charge/proton charge
K^+	K plus	494	+1
K^-	K minus	494	−1
K^0	K zero	498	0
$\bar{K}^0$	K zero bar	498	0
Λ^0	lambda zero	1 116	0
Σ^+	sigma plus	1 189	+1
Σ^0	sigma zero	1 192	0
Σ^-	sigma minus	1 197	−1
Ξ^0	xi zero	1 315	0
Ξ^-	xi minus	1 321	−1

We apologize for the rather unfamiliar symbols that are used to denote these new hadrons. Sometimes Greek letters (such as π and Σ) have been used for hadrons, sometimes Roman letters (such as p and K). It seems that whenever new diversity is discovered, one ends up with a hotch-potch of names and symbols, whose origins are soon forgotten. (For example, few chemists could tell you the historical origin of the symbols for all the elements and there is usually disagreement about the naming of new elements.) The important things about these particles are not their names, but their *properties*. In Table 3 we have given two important properties—the mass (expressed in units of MeV/c^2) and the charge.

charge, in units of proton charge, Q

The charge Q is given in *units of the proton's charge*. It is a remarkable fact that all the particles that have so far been detected have charges that are a multiple of the proton's charge. That means that Q is always a whole number—which may be positive, negative or zero. There is another remarkable thing about the charge Q: it is a *conserved* quantity. That means that the *total charge never changes* in any reaction or decay: it is always the same before and after. For example the strange particles Σ^- and K^+ can be produced in the reaction:

$$
\begin{array}{rccc}
 & \pi^- + p & \longrightarrow & \Sigma^- + K^+ \\
Q\!: & -1 + 1 & = & -1 + 1
\end{array}
$$

conservation of Q

Beneath each particle we have written the charge Q. You can see that it is conserved in this reaction.

ITQ 8 Which one of the following suggested reactions is *impossible*, because it would *not* conserve charge?

(i) $\pi^- + p \longrightarrow n + \pi^0$
(ii) $\pi^- + p \longrightarrow \Sigma^0 + K^0$
(iii) $\pi^+ + p \longrightarrow \Sigma^+ + K^+$
[✓ (iv)] $\pi^- + n \longrightarrow p + \pi^0$

You can see that the conservation of charge forbids certain interactions and allows others. In the next two Sections you will learn about two more quantities, that are also conserved in the interactions of hadrons. They too help to explain which interactions are and are not observed.

5.5 Baryon number

baryon number *B*

In all the *nuclear* processes you met in Unit 30, there is another quantity that is conserved. In nuclear reactions and decays, the *total number of neutrons and protons* does not change. *Baryon number* is a quantity that high energy physicists have found useful in understanding this and other features of the behaviour of hadrons, such as the neutron and proton.

conservation of *B*

The baryon number of a neutron or proton is defined to be $B = 1$, and the baryon number of a lepton (such as e^-, e^+, ν) or a photon (γ) is defined to be zero. With these assignments, the rule that the total number of neutrons and protons does not change in nuclear processes can be expressed as the *conservation of baryon number*. So, for example, we have:

$$\begin{array}{rcl} & {}^{14}_{6}\mathrm{C} \longrightarrow & {}^{14}_{7}\mathrm{N} + \mathrm{e}^- + \nu \\ B\!: & 14 \quad = & 14 \ + 0 \ + 0 \end{array}$$

$$\begin{array}{rcl} & \mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow & {}^{95}_{39}\mathrm{Y} + {}^{139}_{53}\mathrm{I} + \mathrm{n} + \mathrm{n} \\ B\!: & 1 + 235 \quad = & 95 \ + 139 \ + 1 + 1 \end{array}$$

Note that the baryon number of a nucleus is a quantity that you have already met (in Units 10, 11 and 30): the atomic mass number A. So far this may not look very interesting. Why bother with a new name (conservation of baryon number) for an old idea (the total number of neutrons and protons does not change in nuclear processes)? But things become more interesting when you look outside the realm of nuclear physics and consider the production of pions in strong interactions:

$$\begin{array}{l} \mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^0 \\ \mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{n} + \pi^+ \\ \mathrm{p} + \mathrm{n} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^- \end{array}$$

> **ITQ 9** If we insist on the conservation of baryon number in these reactions, what baryon number must be assigned to a pion?

Pions are assigned $B = 0$, so that baryon number is conserved in the interactions of the 'familiar' hadrons (n, p, π^+, π^0, π^-). For example:

$$\begin{array}{rcl} & \pi^- + \mathrm{p} \longrightarrow & \mathrm{n} + \pi^+ + \pi^- + \pi^0 \\ B\!: & 0 \ + 1 \quad = & 1 + 0 \ + 0 \ + 0 \end{array}$$

But what about the 'strange' hadrons, such as K^+ and Σ^-? If we continue to insist on the conservation of baryon number these must have $B = 0$ and $B = 1$, respectively, so that the observed decay:

$$\begin{array}{rcl} & \mathrm{K}^+ \longrightarrow & \pi^+ + \pi^0 \\ B\!: & 0 \quad = & 0 \ + 0 \end{array}$$

and the observed reaction:

$$\begin{array}{rcl} & \pi^- + \mathrm{p} \longrightarrow & \Sigma^- + \mathrm{K}^+ \\ B\!: & 0 \ + 1 \quad = & 1 \ + 0 \end{array}$$

satisfy the rule that baryon number is conserved. Now you have an example of another hadron, the 'strange' Σ^{-1} particle, that must be assigned $B = 1$, the same value as for a neutron or proton. So baryon number conservation *does* express something different from conservation of the total number of neutrons and protons. In the reaction above, a new hadron, Σ^-, with $B = 1$, is created.

It has proved possible to assign baryon numbers to all the strange hadrons of Table 3 in such a way that baryon number is conserved in *all* their interactions and decays. The assignments of baryon number to the particles you have met so far are as follows:

	PHOTON	γ	$B = 0$
	LEPTONS	$\nu, e^-, e^+, \mu^-, \mu^+$	$B = 0$
HADRONS	MESONS	$\pi^+, \pi^0, \pi^-, K^+, K^-, K^0, \bar{K}^0$	$B = 0$
	BARYONS	$p, n, \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-$	$B = 1$

The leptons and the photon have $B = 0$, but the hadrons are divided into two groups*: *baryons* with $B = 1$, and *mesons* with $B = 0$. The choice of names reflects the difference in masses of baryons and mesons. Baryons (from the Greek for 'heavy') have in general, larger masses than mesons ('middling'), which have, in general, larger masses than leptons ('light'). You might think that this general trend would allow one to replace baryon number by a statement about mass, but there are a few exceptions to the general rule that baryons are heavier than mesons**.

baryon **meson**

The baryon number of a particle can be determined from the reactions and decays in which the particle participates, using the law that baryon number is conserved. It turns out to be possible to assign baryon numbers to particles in such a way that the total baryon number is *always* conserved. This conservation law then enables you to make predictions about which reactions can and cannot occur.

ITQ 10 In 1961 a particle called η^0 (eta zero) was discovered. Given that it can be produced by the *strong* interaction:

$$\pi^- + p \longrightarrow n + \eta^0$$

decide whether it is a baryon, a meson, or a lepton.

ITQ 11 Use the law of conservation of baryon number to decide which of the following processes will never be observed:

(i) $\Sigma^+ \longrightarrow \pi^+ + \eta^0$

(ii) $\pi^- + p \longrightarrow K^- + K^+$

(iii) $\pi^+ + p \longrightarrow p + p$

(iv) $\pi^- + p \longrightarrow \Sigma^- + K^+$

5.6 Strangeness

There is a curious fact about strange hadrons that cannot be explained using the rules we have given so far. In any reaction that starts with pions, protons or neutrons, *strange hadrons are not produced singly*. For example, we find the reaction:

$$\begin{array}{rccc} & \pi^- + p & \longrightarrow & \enclose{circle}{\Sigma^-} + \enclose{circle}{K^+} \qquad \text{(occurs)} \\ B\text{:} & 0 + 1 & = & 1 + 0 \\ Q\text{:} & -1 + 1 & = & -1 + 1 \end{array}$$

in which *two* strange hadrons (Σ^- and K^+) are produced; but never the reaction:

$$\begin{array}{rccc} & \pi^- + p & \not\longrightarrow & \enclose{circle}{\Sigma^-} + \pi^+ \qquad \text{(does } \textit{not} \text{ occur)} \\ B\text{:} & 0 + 1 & = & 1 + 0 \\ Q\text{:} & -1 + 1 & = & -1 + 1 \end{array}$$

---

* To be strictly accurate, we should mention that there are also some hadrons, called antibaryons, with $B = -1$. An example is the antiproton, discovered in 1955, which is mentioned in Section 8.1.

** For example, there is a meson called ψ ('psi') which you will meet in Section 9. It is *heavier* than the proton, but the way it is produced shows that it must be a meson, with $B = 0$.

in which only one strange hadron (Σ^-) is produced, despite the fact that the latter reaction appears to be allowed by the laws of conservation of baryon number and charge.

It is almost a working principle of high energy physics that 'anything which is not forbidden will actually happen'. The converse is that when a theorist is confronted with evidence that a suggested process does *not* happen, he will search for a new rule that *forbids* this process, whilst still allowing all those processes that do happen. The puzzle presented by strange hadrons is not confined to this particular example. In Table 4a we give a list of some reactions which *are* observed, and in Table 4b we give a list of some which are *not*. Baryon number and charge are conserved in all the reactions of Table 4a *and* in all the suggested reactions of Table 4b. So what forbids those in the second Table?

TABLE 4a These reactions occur:

(a) $\pi^- + p \longrightarrow \Sigma^- + K^+$

(b) $\pi^+ + n \longrightarrow \Sigma^0 + K^+$

(c) $\pi^+ + n \longrightarrow \Lambda^0 + K^+$

(d) $\pi^+ + p \longrightarrow \Sigma^+ + K^+$

(e) $K^- + p \longrightarrow \Sigma^- + \pi^+$

(f) $K^- + p \longrightarrow \Xi^- + K^+$

(g) $K^- + p \longrightarrow \Xi^0 + K^+ + \pi^-$

TABLE 4b. These reactions do *not* occur:

(a) $\pi^- + p \not\longrightarrow \Sigma^- + \pi^+$

(b) $\pi^+ + n \not\longrightarrow n + K^+$

(c) $\pi^+ + n \not\longrightarrow \Lambda^0 + \pi^+$

(d) $\pi^- + p \not\longrightarrow \Sigma^+ + K^-$

(e) $K^+ + p \not\longrightarrow \Sigma^+ + \pi^+$

(f) $K^- + p \not\longrightarrow \Xi^- + \pi^+$

(g) $K^- + p \not\longrightarrow \Xi^0 + K^+ + K^-$

What is required is some simple, but general, rule that forbids the reactions of Table 4b, whilst allowing the reactions of Table 4a. Progress in making sense of the diversity of hadrons can be dated from the discovery of this rule, around 1953. The rule is that there is a *new property of hadrons* that distinguishes the strange hadrons from protons, neutrons and pions, and that is *conserved* in the strong interactions of hadrons.

You may think that this rule sounds very vague, but we shall now show that it is quite sufficient to forbid all the reactions of Table 4b, whilst allowing those of Table 4a. The proof of the pudding is in the eating!

strangeness *S*

This new property of hadrons is called *strangeness* and is given the symbol S. The first thing we must do is to decide what values of S to assign to 'familiar' hadrons (n, p, π^+, π^0, π^-). Because we do not need a new rule to forbid any reactions that involve *only* these familiar hadrons, we can assign them $S = 0$. Then strangeness will automatically be conserved in strong interactions that do not involve strange hadrons. For example

$$\begin{array}{lccr} & p + p \longrightarrow & p + n + \pi^+ & (\textit{strong}\ \text{interaction}) \\ S: & 0 + 0 \quad = & 0 + 0 + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

Next we have to decide what values of S to assign to the strange hadrons. Let us start with just one of them, the K^+ meson*. What value of S shall we assign to it?

---

* We could start with any strange hadron and assign it any value of S without affecting the conclusion: conservation of strangeness and the observed reactions of Table 4a forbid those of 4b. If you have time, you might later find it a useful revision exercise to repeat the analysis of ITQs 12 and 13, starting with the assignment of $S = -1$ to the Σ^+ baryon.

Well, it doesn't really matter, as long as $S \neq 0$. The units in which we express strangeness won't affect whether it is conserved or not. So let's say that we use units in which K^+ has $S = +1$. The law of conservation of strangeness now tells us the values of S for *all* the strange particles of Table 4a! For example, the first reaction of Table 4a forces us to conclude that Σ^- has $S = -1$. That is the *only* way to ensure conservation of strangeness.

conservation of *S*

To show how this works, let's denote the strangeness of Σ^- by $S(\Sigma^-)$. Then the conservation of strangeness tells us that:

$$\begin{array}{lcll} \pi^- + p & \longrightarrow & \Sigma^- \quad + K^+ & \quad (\textit{strong}\text{ interaction}) \\ S\text{:}\; 0 \;+ 0 & = & S(\Sigma^-) + 1 & \quad (\textit{conserves}\text{ strangeness}) \end{array}$$

and hence

$$0 = S(\Sigma^-) + 1$$

so

$$S(\Sigma^-) = -1$$

ITQ 12 Show that the remaining reactions of Table 4a require the following values:

$$\begin{array}{lll} S(\Sigma^0) = -1 & S(\Lambda^0) = -1 & S(\Sigma^+) = -1 \\ S(K^-) = -1 & S(\Xi^-) = -2 & S(\Xi^0) = -2 \end{array}$$

Now comes the acid test. Can we show that *all* of the suggested reactions of Table 4b are forbidden by the law of conservation of strangeness? Let's try it with the first entry:

$$\begin{array}{lcll} \pi^- + p & \not\longrightarrow & \Sigma^- + \pi^+ & \quad (\text{does } \textit{not} \text{ occur}) \\ S\text{:}\; 0 \;+ 0 & \neq & -1 + 0 & \quad (\text{strangeness } \textit{changes}) \end{array}$$

Well, that one worked! We can now say that this reaction is not observed *because* it does not conserve strangeness.

ITQ 13 Use the values of S assigned to K^+ and derived in ITQ 12 for the other strange hadrons to show that all the remaining reactions of Table 4b are forbidden by the law of conservation of strangeness.

That, surely, is a remarkably neat solution to the problem that was set by the observed reactions of strange particles. We used a few reactions to derive the values of S, and now we can use these values, together with the values of B and Q, to say whether *any* suggested reaction involving the particles of Table 4a is a possible strong interaction.

There are a huge number of predictions we can now make, which can be tested by observing reactions in bubble chambers. If one of these predictions fails, because a reaction that does *not* conserve strangeness is observed, we will know that this new rule must be abandoned. If, on the other hand, we find that some reactions that conserve B, Q and S *cannot* be observed, no matter how hard the experimenters look for them, we will have to play the same game all over again, and try to find another rule, involving a fourth property of hadrons*.

The conclusion of this analysis is that *strangeness is a property of hadrons* which, like baryon number and charge, is *conserved in the strong interactions of hadrons.*

But there is crucial *difference* between strangeness on the one hand and baryon number and charge on the other. You know that B and Q are conserved in *all* processes, but we have not, as yet, looked to see whether strangeness is conserved in the *decays* of strange hadrons. It turns out that it is *not* always conserved. There are *some* decays of hadrons in which the strangeness *changes by one unit*. Such decays are called *weak* decays. An example is:

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* In Section 9 you will learn about a fourth property of hadrons, called 'charm', whose existence was actually *predicted* before any 'charmed' hadrons had been detected.

weak decay

$$\begin{array}{lccclr} & \Sigma^- & \longrightarrow & n + \pi^- & & (\textit{weak}\ \text{decay}) \\ B: & 1 & = & 1 + 0 & & (\textit{conserves}\ \text{baryon number}) \\ Q: & -1 & = & 0 - 1 & & (\textit{conserves}\ \text{charge}) \\ S: & -1 & \neq & 0 + 0 & & (\text{but strangeness}\ \textit{changes}) \end{array}$$

There are two reasons why this decay is called a *weak* decay. First of all, the Σ^- baryon has a much longer half-life than its close relative the Σ^0 baryon. Σ^0 has a decay that conserves strangeness and that produces a photon:

$$\begin{array}{lccclr} & \Sigma^0 & \longrightarrow & \Lambda^0 + \gamma & & (\textit{electromagnetic}\ \text{decay}) \\ B: & 1 & = & 1 + 0 & & (\textit{conserves}\ \text{baryon number}) \\ Q: & 0 & = & 0 + 0 & & (\textit{conserves}\ \text{charge}) \\ S: & -1 & = & -1 + 0 & & (\textit{conserves}\ \text{strangeness}) \end{array}$$

The decay of Σ^0 is called an electromagnetic decay because it produces a photon, and photons (as remarked in Section 4.4) are intimately related to the existence of electromagnetic forces and interactions. Since the decay of Σ^- is 10^9 times slower than that of Σ^0, the choice of the adjective weak to describe Σ^- decay is a reasonable one.

electromagnetic decay

But there is a second and more profound reason for calling Σ^- decay a weak decay. It is believed that the laws that govern Σ^- decay are the same as those that govern the *weak interactions* of neutrinos, which were mentioned in Section 4.4. You may find it puzzling that physicists have devised laws that can describe both the decays of particles and their interactions. But the discussion of the difference between the Newtonian idea of a *force* and the quantum theory of a high energy *interaction*, which was given in Section 4.4, may have prepared you for this new way of thinking. As in Section 4.4, we cannot write down for you the equations that express the quantum theory of weak interactions and decays. We can only tell you which processes do and do not occur and what rules they satisfy. But the intimate connection between interactions and decays is partially revealed by the following list of processes:

(i)
$$\begin{array}{lcccr} & \Sigma^- & \longrightarrow & n + \pi^- & (\textit{weak}\ \text{decay; half-life}\ 1.0 \times 10^{-10}\,\text{s}) \\ S: & -1 & \neq & 0 + 0 & (\text{strangeness}\ \textit{changes}\ \text{by one unit}) \end{array}$$

(ii)
$$\begin{array}{lcccr} & \nu + p & \longrightarrow & e^+ + \Sigma^0 & (\textit{weak}\ \text{interaction}) \\ S: & 0 + 0 & \neq & 0\ \ -1 & (\text{strangeness}\ \textit{changes}\ \text{by one unit}) \end{array}$$

(iii)
$$\begin{array}{lcccr} & n & \longrightarrow & p + e^- + \nu & (\textit{weak}\ \text{decay; half-life}\ 0.6 \times 10^{3}\,\text{s}) \\ S: & 0 & = & 0 + 0\ \ + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

(iv)
$$\begin{array}{lcccr} & \nu + p & \longrightarrow & e^+ + n & (\textit{weak}\ \text{interaction}) \\ S: & 0 + 0 & = & 0\ \ + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

(v)
$$\begin{array}{lcccr} & \Sigma^0 & \longrightarrow & \Lambda^0 + \gamma & (\textit{electromagnetic}\ \text{decay; half-life}\ 10^{-19}\,\text{s}) \\ S: & -1 & = & -1\ \ + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

(vi)
$$\begin{array}{lcccr} & e^- + p & \longrightarrow & e^- + \Sigma^0 + K^+ & (\textit{electromagnetic}\ \text{interaction}) \\ S: & 0\ \ + 0 & = & 0\ \ -1\ \ +1 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

(vii)
$$\begin{array}{lcccr} & \Sigma^{*-} & \longrightarrow & \Lambda^0 + \pi^- & (\textit{strong}\ \text{decay; half-life}\ 1.3 \times 10^{-23}\,\text{s}) \\ S: & -1 & = & -1 + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

(viii)
$$\begin{array}{lcccr} & \pi^- + p & \longrightarrow & \Sigma^- + K^+ & (\textit{strong}\ \text{interaction}) \\ S: & 0\ \ + 0 & = & -1 + 1 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

Please do *not* try to memorize these eight processes. They are written down here only to give examples of the following two rules:

(a) In a weak process (interaction or decay) strangeness may change by one unit *or* it may be conserved. (See (i)–(iv) above.)

(b) In an electromagnetic or strong process (interaction or decay) strangeness is *always* conserved. (See (v)–(viii) above.)

That means that a weak decay may involve a change of strangeness (i), or it may not (iii). Similarly, the weak interactions of neutrinos sometimes involve a change of strangeness (ii), but sometimes do not (iv). But in each of (v)–(viii) there is *no* change in the total strangeness, because these are either electromagnetic processes (v) and (vi); or strong processes (vii) and (viii).

There are a few additional points to note about the examples given above.

1 Leptons and the photon are assigned $S = 0$, just as they are assigned $B = 0$.

2 The strange mesons K^0 and $\bar{K}^0$ have not been assigned values of S in the development so far.

Historically, there were difficulties in deciding what values of S should be assigned to these two mesons, because of the problem of distinguishing between them. The neutral K mesons were not really sorted out properly until 1956, and it is difficult to do justice, in this Unit, to their special features. For the purposes of our discussion, we can say that there are two particles, of the same mass, the K^0 with $S = +1$, and the $\bar{K}^0$ with $S = -1$. Thus K^0 can be produced in much the same manner as K^+:

$$\pi^- + p \longrightarrow \Sigma^0 + K^0 \qquad (\textit{strong}\text{ interaction})$$

$$S:\quad 0 + 0 \quad = \quad -1 + 1 \qquad (\textit{conserves}\text{ strangeness})$$

Whereas $\bar{K}^0$ is most readily produced by a beam of K^- mesons:

$$K^- + p \longrightarrow n + \bar{K}^0 \qquad (\textit{strong}\text{ interaction})$$

$$S:\quad -1 + 0 \quad = \quad 0 - 1 \qquad (\textit{conserves}\text{ strangness})$$

3 Example (iii) involves neutron decay. *Free* neutrons decay with a half-life about 10 minutes:

$$n \longrightarrow p + e^- + \nu + 0.8\,\text{Mev} \qquad (\text{observed } \beta\text{-decay})$$

But the neutrons *in stable nuclei* (such as $^{12}_{6}C$) obviously do not decay, otherwise the nuclei would not be stable, but would undergo β^--decay. The β^--decay of a free neutron is a possible process because it involves a *decrease* in mass of 0.8 MeV/c^2 and hence, according to Section 3.2, a *release* of kinetic energy of 0.8 MeV. But the β^--decay:

$$^{12}_{6}C \not\longrightarrow {}^{12}_{7}N + e^- + \nu - 17.4\,\text{MeV} \quad (\text{no such } \beta^-\text{-decay})$$

is *not* observed. It would have to involve an *increase* in mass of 17.4 MeV/c^2 and hence a *decrease* in kinetic energy of 17.4 MeV. But $^{12}_{6}C$ *at rest* has *zero* kinetic energy and you cannot get less kinetic energy than zero! Hence $^{12}_{6}C$ at rest is stable; so is $^{12}_{6}C$ on the move. You can slow down the rate at which *unstable* particles decay by making them move fast ('moving clocks run slow') but you cannot make a *stable* particle become unstable merely by moving it!

4 For convenience, we have collected information about all the hadrons mentioned so far, in Table 5. This Table also includes some more hadrons, which will figure in Section 6. Table 5 is for reference only. *Do not attempt to commit the details to memory.* The Table is there precisely because we do not want you to have to do this!

Table 5 is on the fold-out page (71a) at the end of this text.

strong decay

The example of a *strong decay* (example (vii))

$$\begin{array}{lcccr} & \Sigma^{*-} & \longrightarrow & \Lambda^0 + \pi^- + 129\,\text{MeV} & (\textit{strong}\ \text{decay}) \\ S: & -1 & = & -1 + 0 & (\textit{conserves}\ \text{strangeness}) \end{array}$$

is drawn from Table 5. The strange hadron Σ^{*-} (sigma star minus) is in some ways very much like Σ^- (sigma minus). It belongs to a family of three particles with $B = 1$, $Q = +1, 0$, or -1, and $S = -1$. But the Σ^{*-} baryon is 188 MeV/c^2 heavier than the Σ^- baryon. And that means that it can decay in Λ^0 and π^-, releasing 129 MeV of kinetic energy. The Σ^- baryon *cannot* decay like this, because this would involve a *decrease* in kinetic energy of 59 MeV, which is impossible in a *decay*. The difference in mass of Σ^{*-} and Σ^- thus makes a huge difference to the half-life. On average, Σ^- at rest lives about 10^{13} times longer than Σ^{*-} at rest, because the decay:

$$\begin{array}{lcccr} & \Sigma^- & \longrightarrow & \text{n} + \pi^- & (\textit{weak}\ \text{decay}) \\ S: & -1 & \neq & 0 + 0 & (\text{strangeness}\ \textit{changes}) \end{array}$$

is a *weak* decay (half-life of order of 10^{-10} seconds) in which strangeness *changes*, whereas the decay of Σ^{*-} is a *strong* decay (half-life of order 10^{-23} seconds) in which strangness is *conserved*.

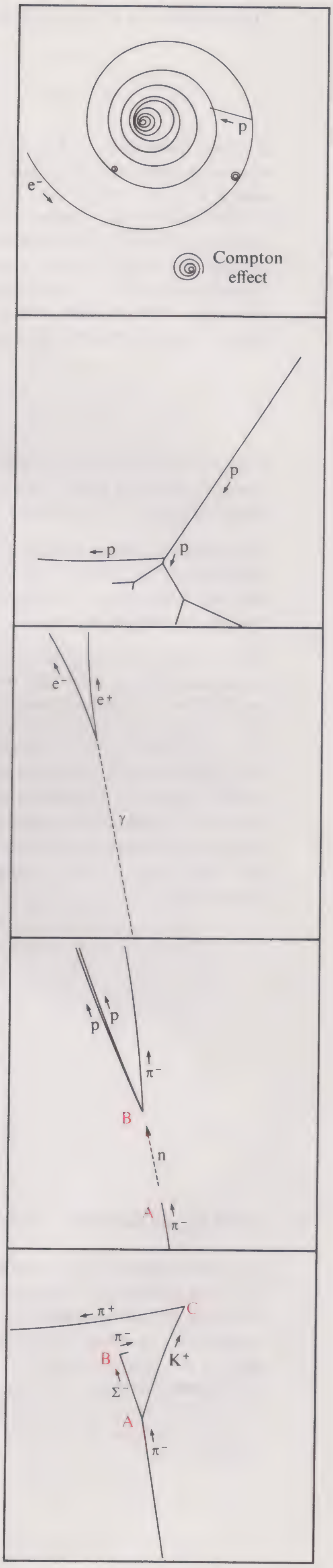
That completes the discussion of strangeness. The important thing to remember is that strangeness is like baryon number and charge, in that it is conserved in strong and electromagnetic interactions and decays, but unlike them, in that it sometimes changes by one unit in weak interactions and decays.

You may be wondering whether the concept of strangeness can be put on a more fundamental basis. After all, we have 'invented' it to devise rules to explain or predict how strange hadrons are created, interact and decay. But strangeness does not explain why there are strange hadrons in the first place (any more than baryon number explains why there are baryons or charge explains why there are charged particles!) In Section 8 we shall describe the quark model of hadrons, which reduces the problem of why there are many 'strange hadrons' to the problem of why there is one 'strange quark'. But for the time being, take a rest from the hard work of trying to follow how high energy physicists use their strange vocabulary and have a look at some of the evidence which fathered the idea of strangeness.

5.7 Looking at pictures (Audio-vision sequence)

Now is the time to take a look at some bubble-chamber photographs, to see if you can find visual evidence for some of the processes we have discussed. Because several photographs of the same tracks can be taken from different angles, we can actually provide you with stereoscopic views of the bubble chamber. In the diagrams that follow in the text, you will find a thumb-nail sketch to direct your attention to the important features of the stereophotographs that are discussed in the Audio-vision sequence entitled 'Bubble-chamber photographs' on audio cassette AC195. We have also indicated the reactions that are being studied.

Film strip 31.1–31.2



p
e⁻
Compton effect
p
p
p
e⁻
e⁺
γ
p
p
π⁻
B
n
A
π⁻
π⁺
C
π⁻
B
K⁺
Σ⁻
A
π⁻

AV1

Spiralling electron

Proton track

Compton effect

AV2

Proton scattering

AV3 Creation of electron and positron

$$\gamma + p \longrightarrow p + e^- + e^+$$

AV4 Interactions of π^- and neutron

A: $\pi^- + p \longrightarrow n + \pi^0$

B: $n + p \longrightarrow p + p + \pi^-$

AV5 Production and decay of strange hadrons

A: $\pi^- + p \longrightarrow \Sigma^- + K^+$

B: $\Sigma^- \longrightarrow n + \pi^-$

C: $K^+ \longrightarrow \pi^+ + \pi^0$

5.8 Summary: assorted hadrons

Section 5 contains quite a few new ideas, so it is important that you should concentrate on the main points.

First of all, there are three essential ingredients of a high energy physics experiment: an accelerator, a way of separating particles into suitable beams, and a device (such as a bubble chamber) to detect the reactions and decays of particles. Accelerators are large and costly machines, because you need a long linear accelerator, or a synchrotron of large radius, to achieve the high energies at which electrons or protons can create new hadrons when they collide with a target. The methods of sorting out these new particles into beams are complicated and need not concern you. One way of detecting *charged* particles is by the tracks of bubbles they leave when passing through liquid hydrogen that is on the point of boiling.

Next, there are three properties of hadrons that are *conserved* in all the strong interactions between hadrons: the *charge* (Q), *baryon number* (B), and *strangeness* (S). The charge Q is expressed in units of the proton charge and is always a whole number (for example, $+1, 0$, or -1). Baryon number distinguishes *baryons* (heavy hadrons with $B = 1$) from *mesons* (lighter hadrons with $B = 0$). Leptons have $B = 0$, but are distinguished from mesons by being even lighter in mass and by having *no* strong interactions. With these assignments B, like Q, is conserved in *all* processes, i.e. both in reactions and decays. Strangeness S is a property of hadrons which distinguishes the more familiar hadrons p, n, π^+, π^0, π^- (with $S = 0$) from the 'strange' hadrons. You do *not* need to memorize the values of S that are assigned to strange hadrons; you will always be able to refer to tables if you need them. The important things to remember about strangeness are as follows:

(a) Once the K^+ meson has been assigned $S = +1$, all the other values follow from a study of which reactions are observed.

(b) Strangeness is always conserved in *strong* interactions and decays and in *electromagnetic* interactions and decays. All decays in which strangeness *changes* by one unit, or in which *neutrinos* are produced, are *weak* decays, with half-lives of order 10^{-10} seconds, or longer, which is a *long* time compared with the half-lives of particles with electromagnetic decays (10^{-16}–10^{-19} seconds) or strong decays (10^{-23} seconds).

Finally, you have seen features of interactions and decays, revealed by bubble-chamber stereophotographs, which give examples of the conservation of charge and baryon number, of the conservation of strangeness in strong interactions, and of the change of strangeness in weak decays.

For ease of reference, information about 25 assorted hadrons has been collected in the fold-out Table 5 (p. 71a), which is *not* to be committed to memory.

Now check that you can use conservation laws to rule out certain suggested processes (Objective 6).

SAQ 7 Use the values of B, Q and S given in the fold-out Table 5 to cross out any of the following suggested reactions which could *not* be detected in an experiment in which a beam of high energy protons passes through a hydrogen bubble chamber.

(a) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^+ + \pi^-$

(b) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \pi^+ + \pi^+ + \pi^-$

(c) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \pi^+$

(d) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \Sigma^+ + \mathrm{K}^+ + \pi^-$

(e) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \Xi^- + \mathrm{K}^+ + \mathrm{K}^+$

(f) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \Sigma^+$

(g) $\mathrm{p} + \mathrm{p} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{K}^+ + \mathrm{K}^-$

Now check you can relate changes of strangeness to rates of decay (Objective 7).

SAQ 8 To answer this question you will need to refer to the fold-out Table 5.

Import

(a) There are *three* electromagnetic decays in Table 5. Do they conserve strangeness?

(b) There are *nine* strong decays in Table 5. Do they conserve strangeness?

(c) What are the *remaining* decays of Table 5 called?

(d) Do they all conserve strangeness?

(c) What is their common characteristic?

6 Diversity and order

A great diversity of hadrons has been discovered since the advent of particle accelerators. The fold-out Table 5 lists just 25 of the hadrons that had been discovered by 1962. At present several hundred hadrons are known and the list grows every year. Surely not all of these hadrons can be 'fundamental particles'—there are more of them than there are chemical elements. In this Section you will see how the properties of hadrons—their mass, baryon number, charge and strangeness—enable one to arrange hadrons in patterns that reveal an underlying order amidst this diversity. The discovery of this order is somewhat analogous to Mendeleev's discovery of the regularities in the properties of elements, which are expressed by the Periodic Table.

On the basis of the patterns that you will discover for yourself in this Section, a theoretical physicist, Murray Gell-Mann, predicted the existence and properties of one more hadron, in 1962. In Section 7 you will be able to make these predictions yourself and study a bubble-chamber photograph, obtained in 1964, that confirms them. Once again there is an historical parallel: Mendeleev was able to predict the existence and properties of new elements, on the basis of gaps in the Periodic Table. In Section 8 we shall explain why this study of hadrons suggests that *hadrons are not fundamental particles*, but are composite structures, made up of simpler particles that have been given the name *quarks*. The historical parallel is the explanation of atomic and nuclear structure in terms of simpler building blocks: electrons, protons and neutrons. Finally, in Section 9, we shall say a little about *charm*, which is a new property of hadrons that was predicted using the idea of quarks.

To appreciate the regularity revealed by the patterns of hadrons, it is best to discover it for yourself. To do this you will need the sheet of card entitled 'Assorted hadrons for Unit 31', from which counters representing hadrons can be punched out. The text is designed to help you arrive at the patterns analysed by Gell-Mann. If you encounter any problems the commentary on the audio cassette should help you along the way.

6.1 Families of hadrons

quantum numbers of a hadron

The numbers B, Q and S, which describe a hadron, are called *quantum numbers*. Together with the mass M, these quantum numbers give a concise description of the hadron. In Figures 7 and 8 we have arranged the mesons ($B = 0$) and baryons ($B = 1$) of Table 5 in patterns that show which values of Q and S are found to occur and which values of the mass M (in MeV/c^2) are found for any particular values of B, Q and S. Notice that there are sometimes two or three values of M corresponding to the same quantum numbers.

Figures 7 and 8 are a first attempt at making patterns of hadrons. There are three important features to notice. First, there is a tendency to find higher values of the charge Q associated with higher values of the strangeness S. This applies most obviously to the baryons of Figure 8, but there is a hint of the same effect for the mesons of Figure 7. Secondly, if you compare mesons and baryons of the same strangeness, you will see that the highest value of Q is carried by baryons. With $S = 0$ the highest value of Q is $+2$, carried by a baryon of mass 1 235 MeV/c^2. With $S = -1$ the highest value of Q is $+1$ which is carried by two baryons of

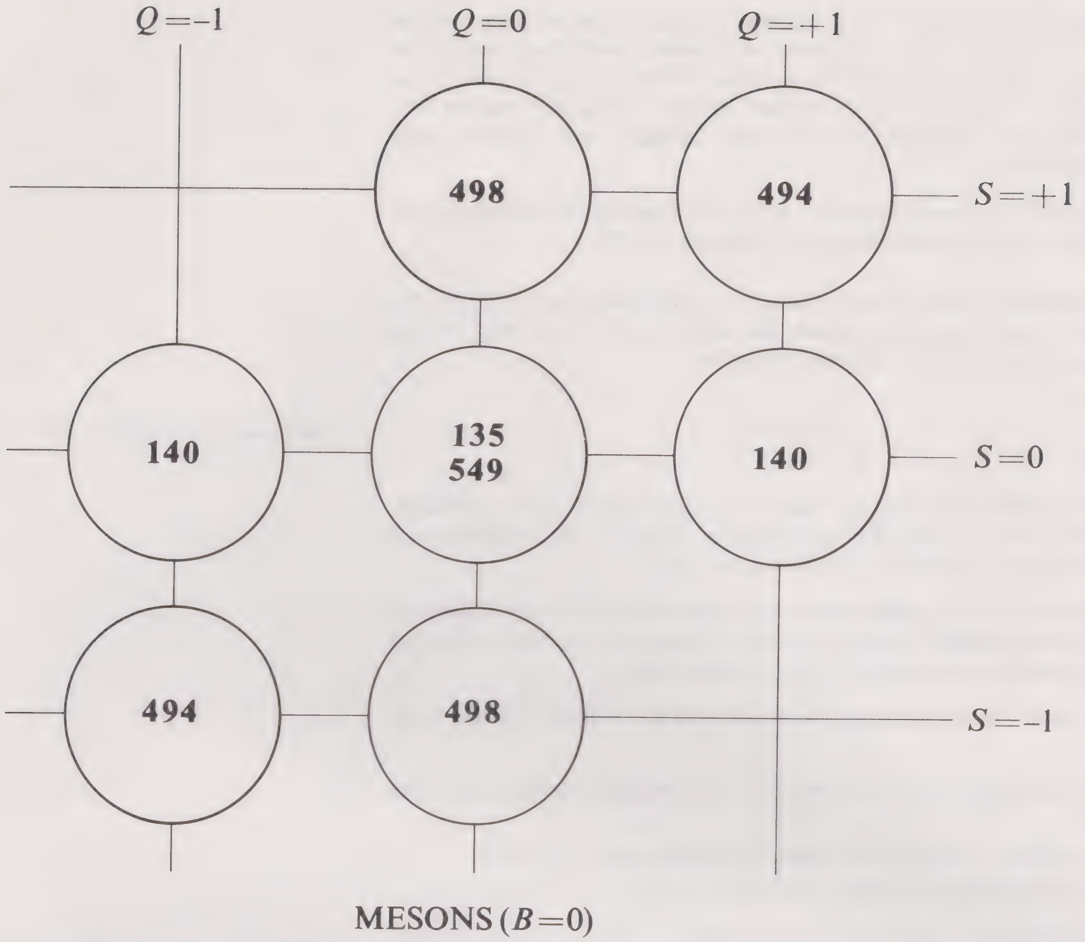

Q=-1
Q=0
Q=+1
498
494
S=+1
140
135
549
140
S=0
494
498
S=-1
MESONS (B=0)

FIGURE 7 The mesons of Table 5.

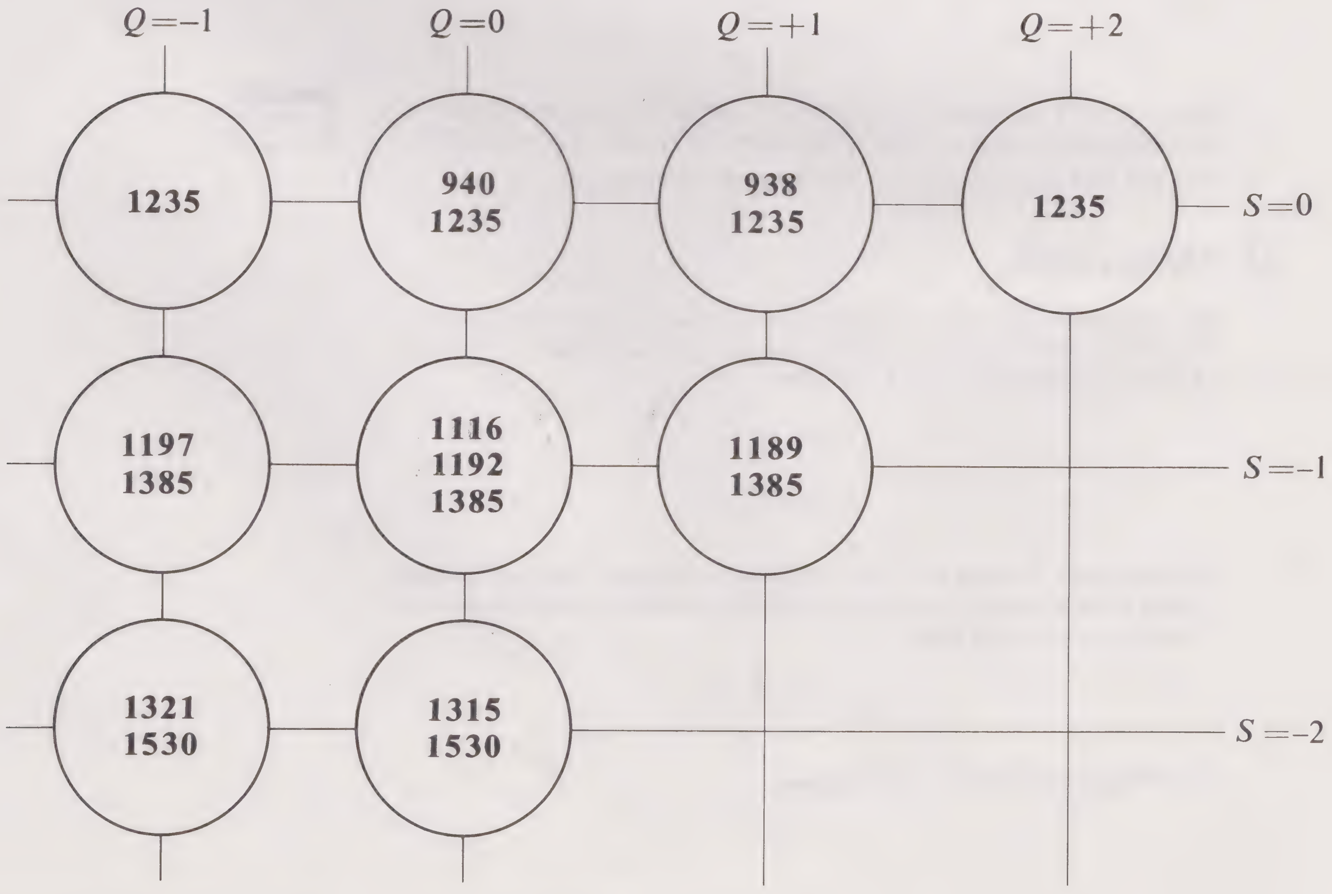

Q=-1
Q=0
Q=+1
Q=+2
1235
940
1235
938
1235
1235
S=0
1197
1385
1116
1192
1385
1189
1385
S=-1
1321
1530
1315
1530
S=-2
BARYONS (B=1)

FIGURE 8 The baryons of Table 5.

masses 1 189 and 1 385 MeV/c^2. The final point to notice is that particles with the same values of B and S can be grouped into families containing particles of different charge, but masses that differ by *less than* 10 MeV/c^2. For example the six baryons with $S = 0$ can be grouped into two families: one family contains four particles with $M = 1\,235$ MeV/c^2, the other contains two particles with $M = 938$–940 MeV/c^2.

These three observations are combined and generalized by the following rule, which was discovered by Gell-Mann and Nishijima in 1953:

> If hadrons are grouped into families, containing particles with the same values of B and S and with masses that differ by less than 10 MeV/c^2, the average charge $\langle Q \rangle$ of a family is given by:

$$\langle Q \rangle = \frac{B + S}{2}$$

Gell-Mann–Nishijima formula

You should now check this formula, using the counters from the sheet provided. In the course of doing so, you will have sorted these counters into the families you will be dealing with in Section 6.2. Here is what to do:

STEP 1 Punch out the 25 counters corresponding to the 25 hadrons of the fold-out Table 5. (The two blank counters are not needed yet.) Place them in front of you with the quantum numbers (B, Q, S) facing *upwards*.

STEP 2 Sort them into two groups: the mesons with $B = 0$ and the baryons with $B = 1$.

STEP 3 Now divide the mesons and baryons into families, according to the following rules:

(i) All the particles in a family must have the same values of B and S.

(ii) Particles in the same family must not differ in mass by more than 10 MeV/c^2.

STEP 4 You should now have four meson families and seven baryon families. Calculate the average charge $\langle Q \rangle$ of each family, by adding up the charges of its members and dividing by the number of members. Do you agree that:

$$\langle Q \rangle = \frac{B + S}{2}$$

for every family? *If you have any difficulty in verifying this relationship, listen to the Audio-vision sequence entitled 'Hadron families' on audio cassette AC195.*

You will need your families later. DO NOT DISTURB THEM.

6.2 Making patterns

The patterns made by hadrons are best displayed using the special graph paper of Figure 9. To decide where to place a counter you will need to calculate the values of the two coordinates X and Y defined by:

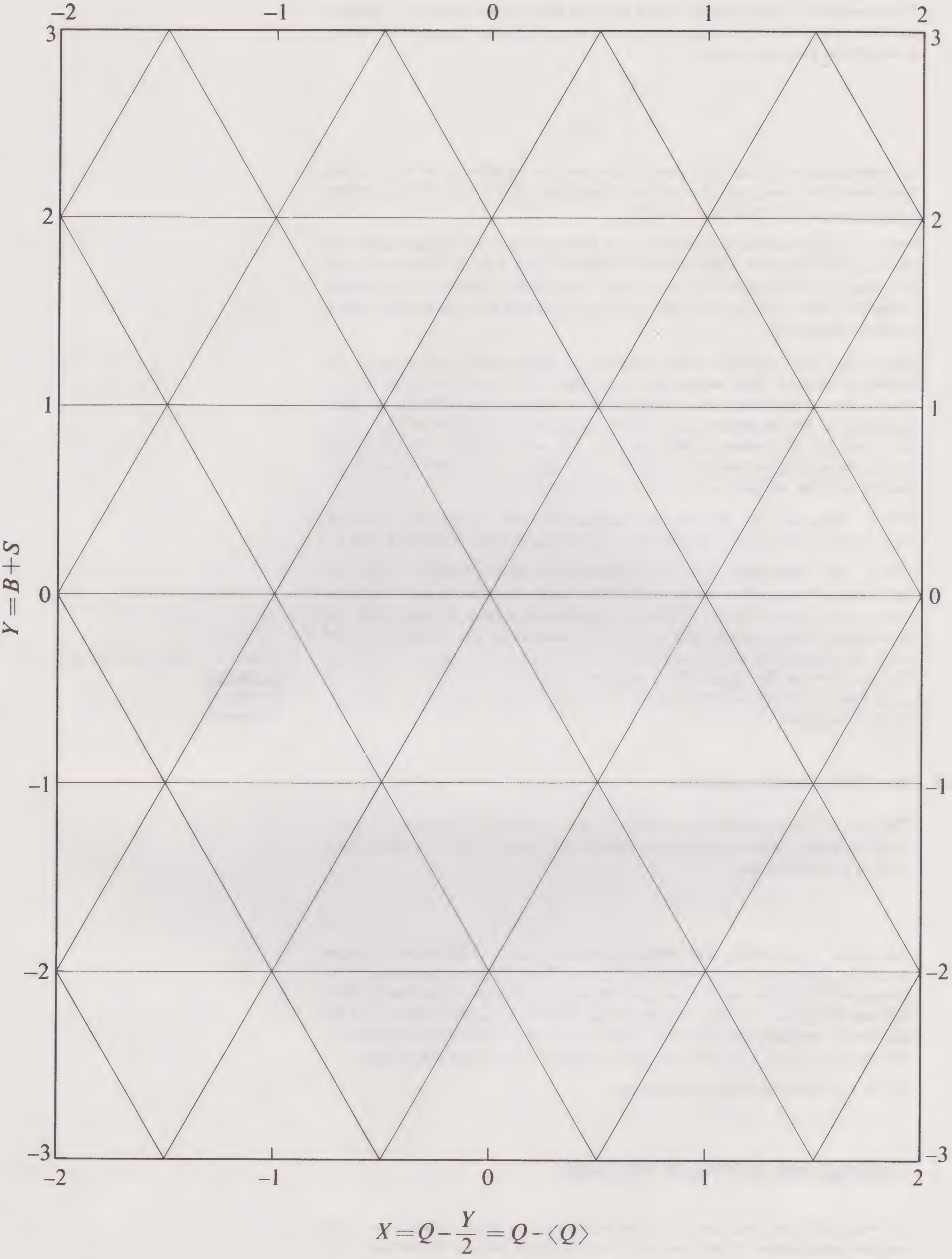
$$Y = B + S$$

$$X = Q - \frac{Y}{2}$$

The coordinate Y, along the *vertical* axis, has been chosen because it is simply related to the average charge $\langle Q \rangle$ of the family to which the hadron belongs. In Section 6.1 you verified that:

$$\langle Q \rangle = \frac{Y}{2} = \frac{B + S}{2}$$

for all the families of mesons and baryons.



−2
−1
0
1
2
3
2
1
0
−1
−2
−3
$Y = B + S$
$X = Q - \frac{Y}{2} = Q - \langle Q \rangle$

FIGURE 9 Special graph paper.

The coordinate X, along the *horizontal* axis, has been chosen because it expresses the difference between the charge of a hadron and the average charge of the family to which the hadron belongs:

$$X = Q - \frac{Y}{2}$$
$$= Q - \langle Q \rangle$$

The advantages of using these coordinates and the significance of the diagonal lines should become apparent when you arrange your counters on the three sheets of graph paper that have been provided.

STEP 5 Arrange all the *meson* counters on a sheet of the special graph paper. To do this you will need to calculate the coordinates X and Y for each meson counter and place it over the point with these coordinates. If two counters have the same values of X and Y, let them overlap. You should find that the eight mesons make a *symmetrical* pattern.

STEP 6 The next job is to make a pattern of baryons that is identical to the pattern of mesons. That means you must select four out of the seven baryon families and arrange them on a second sheet of graph paper, following the same procedure as for the mesons, and end up with a pattern of eight baryons which looks just like the pattern of eight mesons. You will find that there are several ways of doing this, because there are more than eight baryons. *Make your baryon pattern using the baryon families of the lowest possible mass.*

STEP 7 There are now three baryon families left over. Arrange the remaining baryons on a third sheet of graph paper, according to their values of X and Y.

STEP 8 This third pattern is not as symmetrical as the previous ones. Can you find a way of using either one or both of the blank counters, so as to make the pattern more symmetrical? When you have found a way of 'improving the appearance' of the pattern, turn over all the counters on your three sheets and check that they agree with Figures 10, 11 and 12. *If you do not agree with these Figures, listen to the Audio-vision sequence entitled 'Making the patterns' on audio cassette AC195,* which should help you solve any problems you encountered in Steps 5–7.

Figures 10, 11 and 12 are on pp. 46–7.

6.3 Summary: hadron symmetry

The point of this exercise was to show that there is some sort of underlying order in the observed masses and quantum numbers of hadrons. One expression of this order is the relationship:

$$\langle Q \rangle = \frac{B + S}{2} = \frac{Y}{2}$$

discovered by Gell-Mann and Nishijima. Another aspect of this order is that we can make the symmetrical patterns of Figures 10 and 11 (these patterns are also shown in TV programme 31), using all the mesons of Figure 7 and some of the baryons of Figure 8. Finally, you have seen that the remaining baryons are not distributed randomly in Figure 12. *If only* there were another baryon, with coordinates $X = 0$, $Y = -2$, you would have a pattern with triangular symmetry.

But in 1962 no such baryon was known.

7 Making and testing predictions

In 1962 Gell-Mann predicted the existence of a new hadron on the basis of the regularities of hadrons which you discovered in the last Section. Immediately after the announcement of the discovery of the baryons Ξ^{*-} and Ξ^{*0} (displayed in Figure 12 on the line $Y = -1$) he suggested that there should be another baryon, with coordinates $X = 0$ and $Y = -2$, to complete the pattern of Figure 12.

Gell-Mann's belief that the nine known baryons of Figure 12 were part of a triangular pattern of ten baryons was based on more than just a general notion of symmetry. He had found a mathematical expression* of the symmetry of Figures 10 and 11 and the mathematics he had used allowed only certain other patterns, which included the triangular pattern of ten baryons of Figure 12. He felt that there was a good possibility that experimental physicists would be able to confirm or contradict his prediction of a new baryon, and he believed that confirmation would be a very strong indication of the importance of the symmetry arguments that he and other theorists had been trying to develop**. By the same token, experimental contradiction would indicate that these arguments were inadequate, and would serve to direct research along different lines. This should help to explain why Gell-Mann was prepared to make the strongest and most precise predictions possible, *hoping* to be proved correct, but also being prepared to *learn* from experiment. This combination of intelligent optimism and real uncertainty is a hallmark of research at the frontiers of science. That is why we are asking you to make your *own* predictions in this Section, rather than telling you what Gell-Mann predicted. Try to answer as many of the ITQs of Section 7.1 as you can, using what you have learnt about the properties and patterns of hadrons. We advise you *not* to look up the answers *until* you have made your own predictions, because at the frontiers of science there are no 'answers at the back of the Unit'—one must live by one's wits and await the verdict of experiment. Gell-Mann's preparedness to submit to this discipline was rewarded, in 1964, by the experiment described in Section 7.2, and by the award of a Nobel Prize for 'his contributions and discoveries concerning the classification of elementary particles and their interactions' in 1969. We hope that you will enjoy retracing some of the arguments underlying the predictions he made in 1962.

7.1 Predictions

Gell-Mann predicted the existence of a new particle that would correspond to the blank counter which you used to complete the pattern of Figure 12. He denoted it by the symbol Ω, which is the last letter of the Greek alphabet, omega. You can make your own predictions by selecting appropriate items in the following ITQs.

ITQ 14 I predict the existence of a new particle, Ω, which is:

A a lepton

B a meson

C a baryon

ITQ 15 The charge of Ω is indicated by my choice of name:

A omega minus

B omega zero

C omega plus

D omega double plus

ITQ 16 The strangeness of Ω will be determined when it is discovered how it is produced in strong interactions. I predict that it will be found to have strangeness equal to:

A 1

B 0

C −1

D −2

E −3

---

* The branch of mathematics he used is known as 'the theory of continuous transformation groups' which had been developed by a Norwegian mathematician, Marius Sophus Lie, in 1884–93. Gell-Mann recognized that the symmetry of the patterns of Figures 10, 11 and 12 could be expressed in terms of a mathematical structure called SU(3)—'the group of special unitary matrices of rank three'.

** The symmetry of Figures 10 and 11 had also been discovered by Yuval Ne'eman, an Israeli military attaché, as you will hear later on the audio cassette.

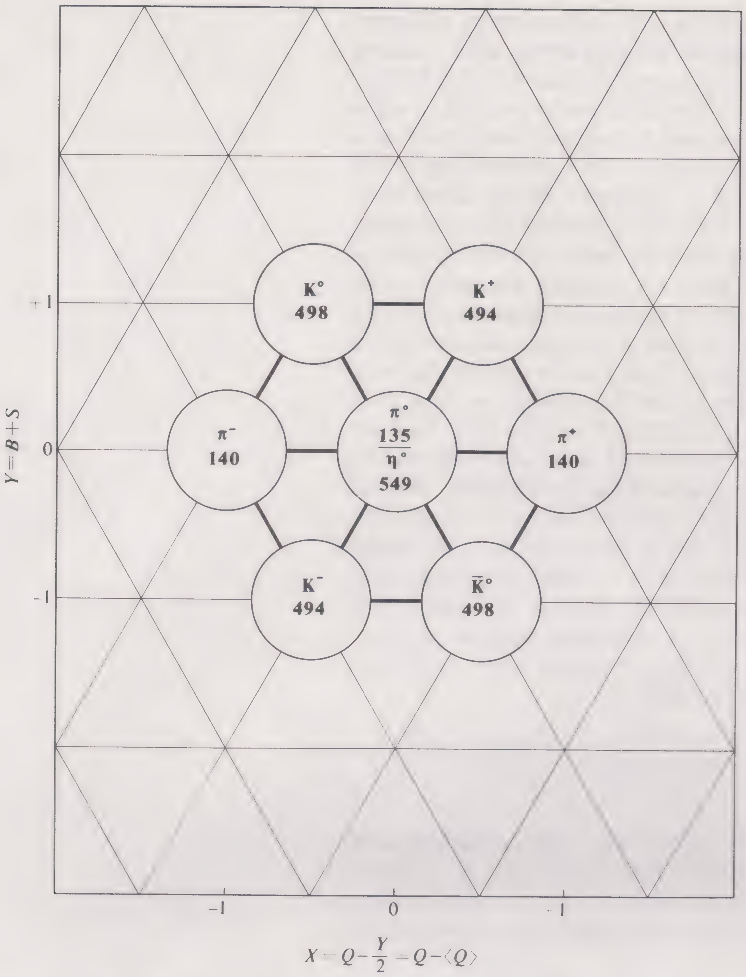

K°
498
K⁺
494
π⁻
140
π°
135
η°
549
π⁺
140
K⁻
494
K̄°
498
+1
0
−1
Y = B + S
−1
0
+1
X = Q − Y/2 = Q − ⟨Q⟩

FIGURE 10 A pattern of eight mesons.

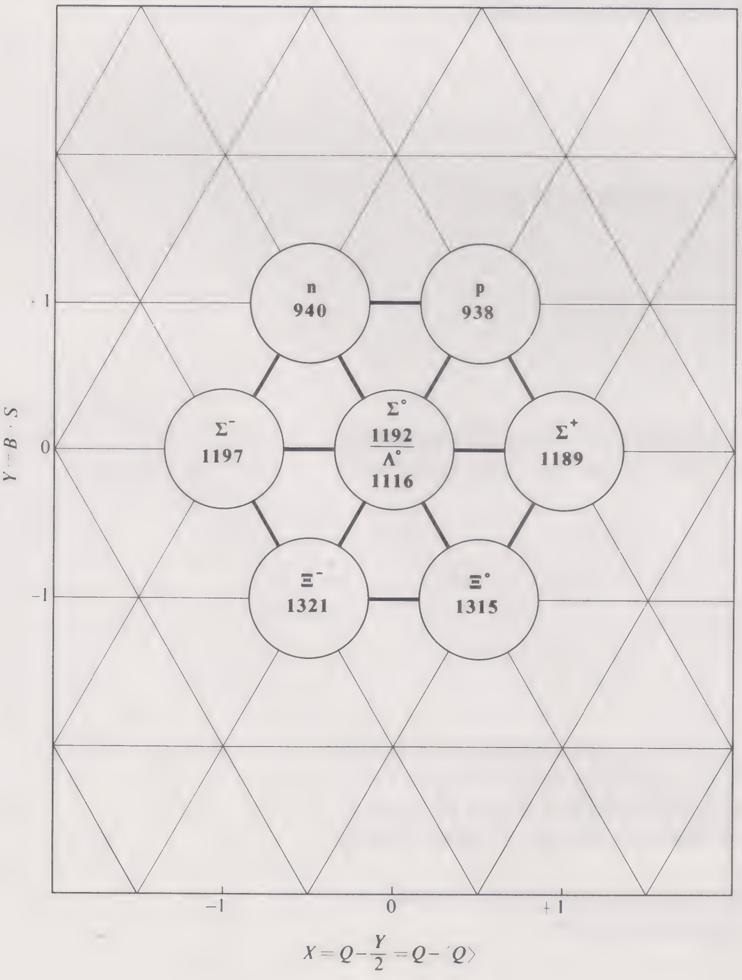

n
940
p
938
Σ⁻
1197
Σ°
1192
Λ°
1116
Σ⁺
1189
Ξ⁻
1321
Ξ°
1315
+1
0
−1
Y = B + S
−1
0
+1
X = Q − Y/2 = Q − ⟨Q⟩

FIGURE 11 A pattern of eight baryons.

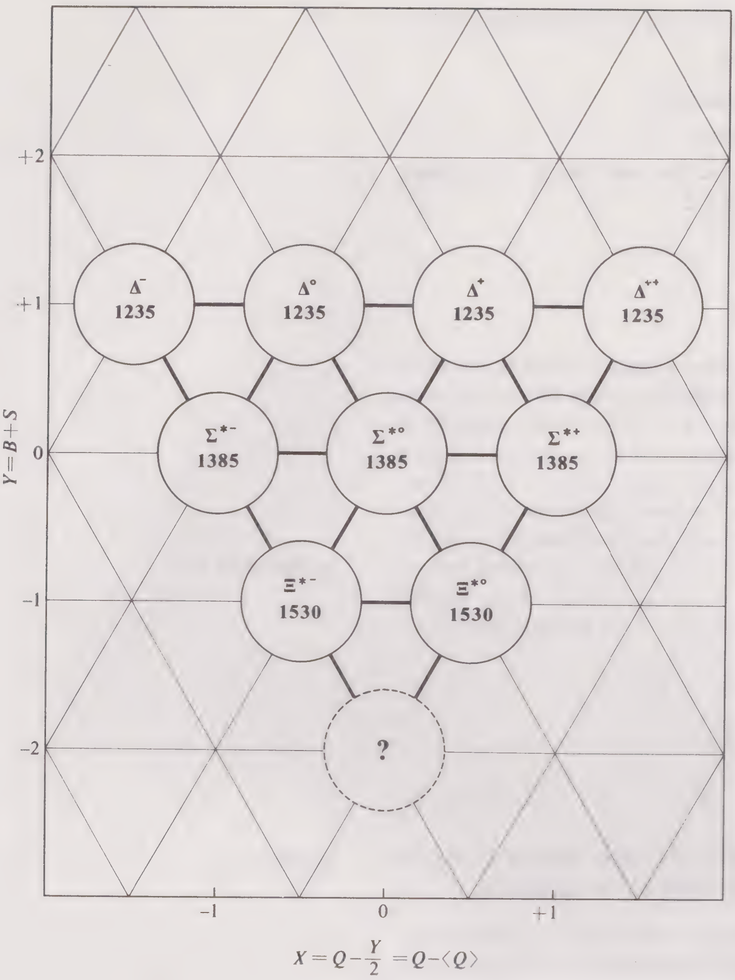

+2
+1
0
−1
−2
$Y = B + S$
Δ^- 1235
Δ^0 1235
Δ^+ 1235
Δ^{++} 1235
Σ^{*-} 1385
Σ^{*0} 1385
Σ^{*+} 1385
Ξ^{*-} 1530
Ξ^{*0} 1530
?
−1
0
+1
$X = Q - \frac{Y}{2} = Q - \langle Q \rangle$

FIGURE 12 A tenth baryon?

ITQ 17 On the basis of the masses of the other baryons in Figure 12, I predict that the mass of Ω will lie in the following range:

A $(1\,550 \pm 30)$ MeV/c^2

B $(1\,610 \pm 30)$ MeV/c^2

C $(1\,670 \pm 30)$ MeV/c^2.

D $(1\,730 \pm 30)$ MeV/c^2

ITQ 18 My predictions of the quantum numbers of Ω allow it to be produced strongly in the following reaction:

A $K^- + p \longrightarrow \Omega + K^+$

B $K^- + p \longrightarrow \Omega + K^+ + K^+$

C $K^- + p \longrightarrow \Omega + \Sigma^+ + K^0$

D $K^- + p \longrightarrow \Omega + K^+ + K^0$

(*Select one item from the key.*)

ITQ 19 My predictions of the mass and quantum numbers of Ω allow it to decay weakly in the following ways:

A $\Omega \longrightarrow n + \pi^-$

B $\Omega \longrightarrow \Lambda^0 + \pi^-$

C $\Omega \longrightarrow \Xi^0 + \pi^-$

D $\Omega \longrightarrow \Xi^- + \pi^0$

E $\Omega \longrightarrow \Lambda^0 + K^-$

F $\Omega \longrightarrow \Sigma^0 + K^-$

(*Select as many items as possible from the key*, bearing in mind that the strangeness cannot change by more than one unit and the total mass cannot increase in such a decay.)

ITQ 20 I predict that Ω particles produced in a bubble chamber will:

A decay before leaving detectable tracks;

B decay long after leaving the bubble chamber;

C leave no tracks, because they are neutral;

D leave detectable tracks between production and decay, in the same manner as do the particles Σ^-, Σ^+, and Ξ^-.

(*Select one item from the key.*)

7.2 Experiment

Gell-Mann found it relatively easy to convince other physicists of the significance of his predictions. In particular Samios, an experimenter from the Brookhaven National Laboratory, near New York, was struck by the beauty and simplicity of the predictions and convinced some of his colleagues of the importance of testing them. Samios and his collaborators did not need to be as brave as Gell-Mann: their work would be of value whether it confirmed *or* contradicted the predictions. But their ingenuity, dedication and patience as experimenters were stretched by the demands of the experiment. They had to search for an omega minus baryon with quantum numbers $B = 1$, $Q = -1$, $S = -3$ and with mass around 1 670 MeV/c^2 (ITQs 14–17) which could be produced in the reaction (ITQ 18):

omega minus Ω^-

$$K^- + p \longrightarrow \Omega^- + K^+ + K^0$$

and decay in one of the following ways (ITQ 19):

$$\Omega^- \longrightarrow \Xi^0 + \pi^- \qquad \Omega^- \longrightarrow \Xi^- + \pi^0 \qquad \Omega^- \longrightarrow \Lambda^0 + K^-$$

after leaving a track in a bubble chamber (ITQ 20). (Note that we have now returned to standard practice by putting a minus sign on the symbol Ω^-.)

prediction of Ω^-

They started in earnest in November 1963, using a beam of K^- mesons and a bubble chamber containing liquid hydrogen. After several months of checking the beam, adjusting magnets and mending leaks, they began to get many photographs of interactions between K^- mesons and protons. By January 1964 they were using several rolls of film a day, with 2 000 pictures on every roll! They ended up with about 100 000 pictures and scanned them intensively, looking for Gell-Mann's 'needle in the haystack'. Finally on roll 53, they found picture 97 025, which we have reproduced (in negative) in Figure 13. To understand their elation, it is best to look at Figure 14, which isolates the features that are relevant, and then study the interpretation given in Figure 15.

First of all a K^- meson collides with a proton, at the point marked A in Figure 15. An omega minus baryon is produced in the manner predicted:

discovery of Ω^-

$$K^- + p \longrightarrow \Omega^- + K^+ + K^0 \qquad \text{(A)}$$

The K^0 meson, being neutral, escaped observation, but the direction it took could be worked out using the law of conservation of momentum. The K^+ meson track can be followed until it leaves the chamber. At the point marked B, Ω^- decays:

$$\Omega^- \longrightarrow \Xi^0 + \pi^- \qquad \text{(B)}$$

Then Ξ^0 decays at C, producing two more neutral particles: Λ^0 and π^0. Almost immediately π^0 decays into two photons:

$$\Xi^0 \longrightarrow \Lambda^0 + \pi^0 \qquad \text{(C)}$$
$$\pi^0 \longrightarrow \gamma + \gamma$$

Fortunately, Λ^0 decays, producing charged particles at D:

$$\Lambda^0 \longrightarrow p + \pi^- \qquad \text{(D)}$$

And each photon from C produces an electron and a positron when it collides with a proton in a hydrogen atom:

$$\gamma + p \longrightarrow p + e^- + e^+ \qquad \text{(E and F)}$$

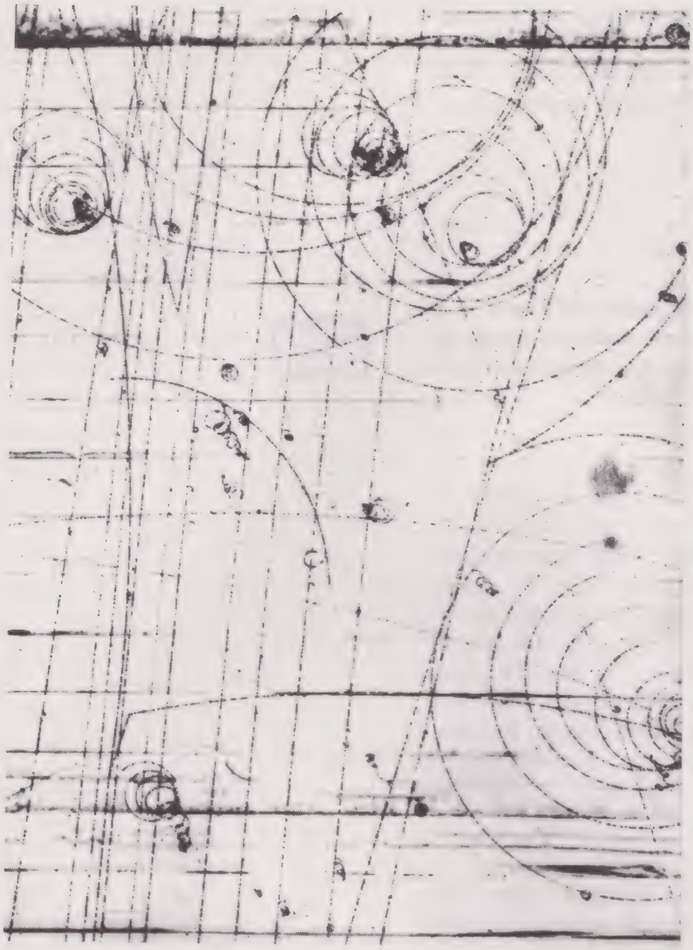


FIGURE 13 Roll 53, picture 97025, in negative.

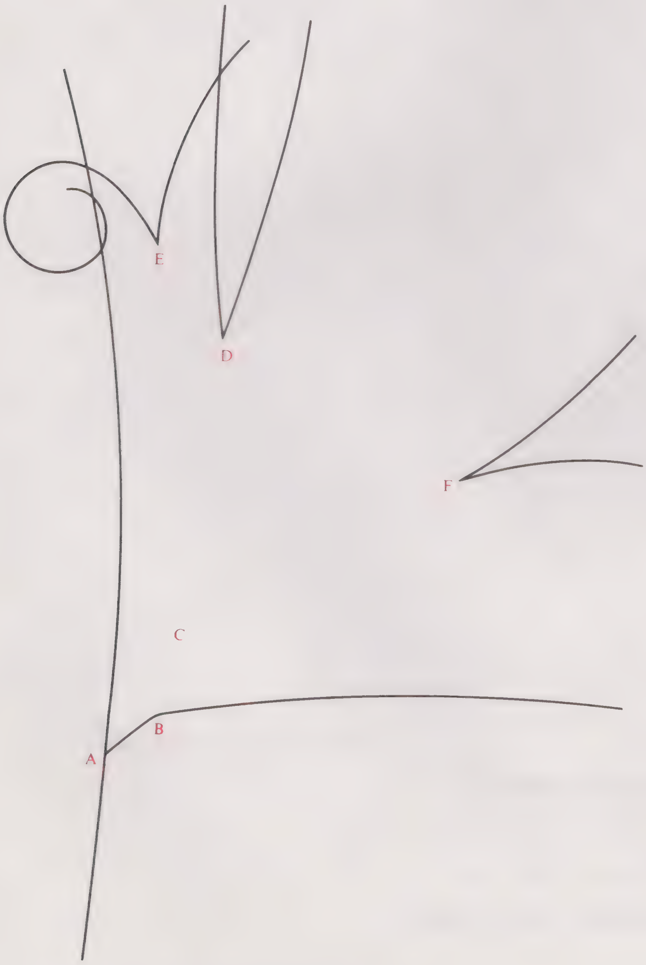


FIGURE 14 Important features.

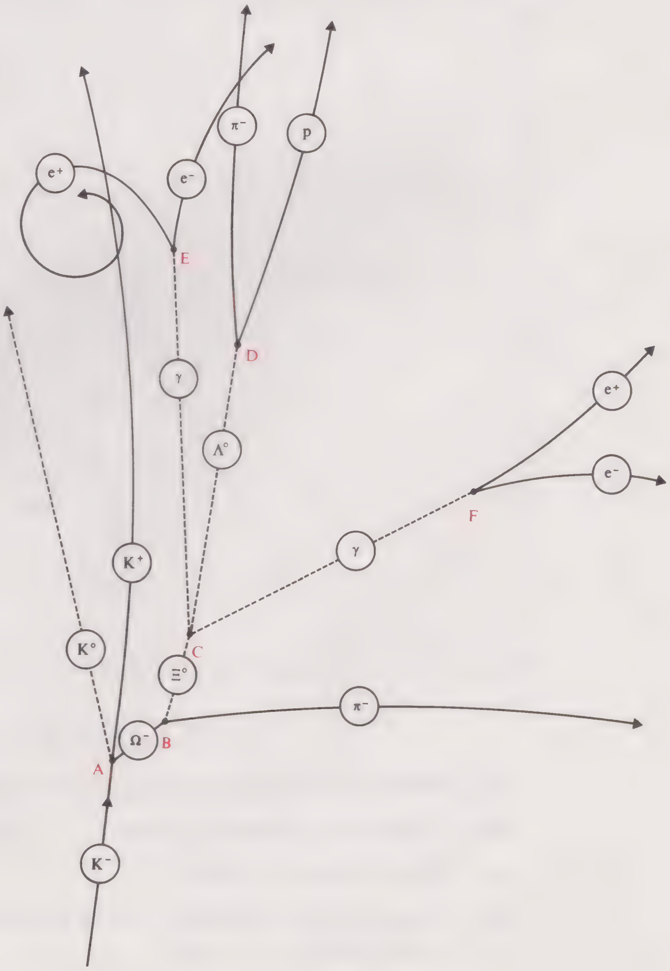

π^-
p
e^+
e^-
E
D
γ
Λ°
e^+
e^-
F
γ
K^+
C
K°
Ξ°
Ω^-
B
π^-
A
K^-

FIGURE 15 Interpretation.

In this and subsequent experiments *all* the predictions of ITQs 14–20 have been confirmed. The mass of Ω^- is now known to be $(1\,672 \pm 1)\mathrm{MeV}/c^2$. In a more recent experiment at CERN about 100 omega minus baryons were observed. All three of the predicted decays of ITQ 19 were seen, in the following proportions:

$$\Omega^- \longrightarrow \Xi^0 + \pi^- \text{ (40 per cent)}$$

$$\Omega^- \longrightarrow \Xi^- + \pi^0 \text{ (5 per cent)}$$

$$\Omega^- \longrightarrow \Lambda^0 + K^- \text{ (55 per cent)}$$

If you would like to hear more about the remarkable prediction and discovery of Ω^- from the scientists involved, listen to the sequence entitled 'The search for the omega minus particle' on audio cassette AC195. This is optional, but highly recommended!

7.3 Summary: successful prediction

You have come a long way in Sections 5, 6 and 7. In Section 5 you learned how to assign the quantum numbers B, Q and S to hadrons, using conservation laws. In Section 6 you discovered the patterns revealed by the masses and quantum numbers of hadrons. Now you have seen that the pattern of Figure 12 *can* be completed, in the simplest possible way, thanks to the experimental confirmation of the prediction of omega minus. We still have not *explained* the diversity of hadrons, but there certainly is an order underlying this diversity. It is difficult to imagine how you could have been led to such a specific and successful prediction without there being some intimate connection between the commonest hadrons, such as the proton and neutron, and the other hadrons that are produced in such variety when enough energy is supplied.

Now see if you make predictions from another pattern (Objective 8).

SAQ 9 In Figure 16 there is another pattern with a missing hadron. The particles whose masses and symbols are indicated are all *mesons*, that have not been mentioned so far.

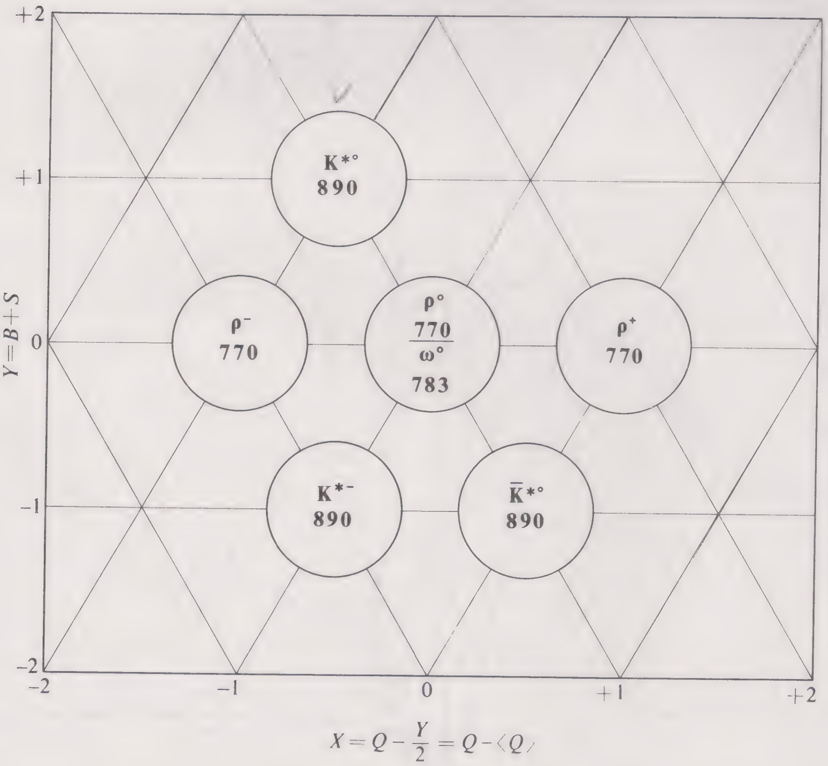


FIGURE 16 An eighth meson?

(a) Predict the mass and quantum numbers of the missing hadron, H.

(b) Could H be produced as follows? $\pi^+ + p \longrightarrow \Sigma^+ + H$

(c) Could H decay as follows? $H \longrightarrow K^0 + \pi^+$

(d) Would H leave a detectable track in a bubble chamber? (*Hint* Does it decay weakly or strongly?)

8 Quarks

The choice of the last letter of the Greek alphabet for Ω^- turned out to be an appropriate one. No new combinations of the quantum numbers B, Q and S have been discovered since 1964. Many more hadrons have been found, but none have quantum numbers which place them outside the triangle of Figure 12. For example the mesons of Figure 16, together with the extra one you predicted in SAQ 9, have the same pattern of quantum numbers as the mesons of Figure 10. The masses are higher, but the quantum numbers are the same*.

An explanation of why these, and only these, combinations of quantum numbers occur was offered by Gell-Mann and, independently, by Zweig, in 1964. They suggested that *hadrons are not fundamental particles* but are made of simpler particles, which Gell-Mann called *quarks***.

quark

8.1 The three-quark model

The quark model of hadrons, at its simplest, specifies:

(a) the number of types of quark;

(b) the quantum numbers of these quarks;

(c) the rules for combining quarks to make hadrons.

The key to understanding how these ingredients were specified is the symmetry of the patterns of hadrons you have found. A common feature of the hexagonal (six-sided) patterns of Figures 10 and 11 and the triangular pattern of Figure 12 is that they can be rotated about the origin ($X = 0$, $Y = 0$) through an angle of 120° without changing the shape of the pattern. (You might like to stick a pin through the centre of one of your patterns and try this.) If we are trying to formulate a model in which hadrons are made of quarks, it makes sense to start with a pattern of quarks that has this symmetry too. The simplest way to do that is to say that there are *three* quarks, and that they have quantum numbers that correspond to coordinates X and Y that place the quarks in a triangular pattern, such as that in Figure 17.

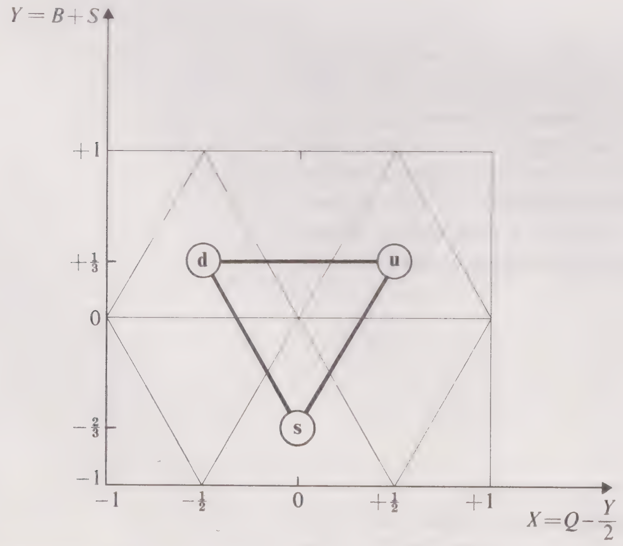


FIGURE 17 Three quarks.

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* The mesons of Figures 10 and 16 are also differentiated by a property called 'spin', which we do not consider in this Unit.

** Zweig suggested the name 'aces', but Gell-Mann's choice has stuck. 'Quark' is pronounced to rhyme with 'hark' by some physicists, but to rhyme with 'walk' by others. It appears as a nonsense word in *Finnegan's Wake*, by James Joyce.

In Figure 17 the three quarks have been chosen so that they make a triangle of the same size as the smallest triangles that appear in the hadron patterns. The origin is at the centre of the triangle, just as the origin was at the centre of the hadron patterns, and the triangle has been chosen pointing downwards, in the same way as the large triangle of Figure 12. This was the choice made by Gell-Mann, and it certainly seems to be the simplest choice that shares as many features as possible with the patterns of hadrons.

three-quark model

We have now specified the number of types of quark: there are *three* in this model. And we are well on the way to specifying their quantum numbers. It is now a simple matter to calculate the charges of the three types of quark. To do this we need the two relations:

$$X = Q - \langle Q \rangle$$

$$\langle Q \rangle = \frac{Y}{2}$$

which give the result:

$$Q = X + \langle Q \rangle = X + \frac{Y}{2}$$

In Table 6 we have calculated the charges of the three quarks, labelled u, d, and s.

TABLE 6 Coordinates and charges of the quarks

	X	Y	$Q = X + \frac{Y}{2}$
u	$+\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$
d	$-\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{1}{3}$
s	0	$-\frac{2}{3}$	$-\frac{1}{3}$

But notice what has happened: we have got charges that are *not* whole numbers. How can we make baryons with charges of +2, +1, 0 and −1 out of quarks with charges of $+\frac{2}{3}$, $-\frac{1}{3}$ and $-\frac{1}{3}$? That's easy! We can formulate the model by saying that a baryon is made of three quarks. So combining three u quarks will give a baryon with $Q = +2$, but two u quarks and a d quark will give a baryon with $Q = +1$, and so on. But what then is the baryon number of a quark? It must be $B = \frac{1}{3}$, because three quarks make a baryon with $B = 1$. And now we know that $B = \frac{1}{3}$ we can calculate the values of the strangeness S, using the definition of the coordinate Y.

$$Y = B + S$$

hence

$$S = Y - B = Y - \tfrac{1}{3}$$

That means that the u and d quark (with $Y = +\frac{1}{3}$) must have $S = 0$, but the s quark (with $Y = -\frac{2}{3}$) must have $S = -1$. For that reason, s was called the *strange quark*. The non-strange quarks u and d were called the *up quark* and the *down quark*. They are distinguished by their charges: the up quark, u, has $Q = +\frac{2}{3}$ and the down quark, d, has $Q = -\frac{1}{3}$*.

So the simple triangle of Figure 17 has led to the following model:

---

* Hence the charge of a baryon goes *up* by one unit if you replace a down quark by an *up* quark.

Quark model of baryons

(a) There are *three* types of quark: up (u), down (d) and strange (s).

(b) Their quantum numbers are:

	Q	B	S
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1

(c) A baryon consists of three quarks.

So let us see what combinations of quantum numbers baryons can have in this model. In Table 7 we have calculated the quantum numbers of all the possible combinations of quarks.

TABLE 7 A baryon is made of three quarks

Combination	B	Q	S	Baryons		
(uuu)	1	+2	0	Δ^{++}		
(uud)	1	+1	0	Δ^{+}	p	
(udd)	1	0	0	Δ^{0}	n	
(ddd)	1	−1	0	Δ^{-}		
(uus)	1	+1	−1	Σ^{*+}	Σ^{+}	
(uds)	1	0	−1	Σ^{*0}	Σ^{0}	Λ^{0}
(dds)	1	−1	−1	Σ^{*-}	Σ^{-}	
(uss)	1	0	−2	Ξ^{*0}	Ξ^{0}	
(dss)	1	−1	−2	Ξ^{*-}	Ξ^{-}	
(sss)	1	−1	−3	Ω^{-}		

Every baryon you know of can be associated with a combination of quarks and every combination of quarks can be associated with at least one baryon you know of. That is certainly very encouraging.

And finally, how can we explain the fact that several baryons, with different masses, can be built out of the same combination of quarks? For example both Σ^0 and Λ^0 are supposed to consist of (uds). Well, you have met examples of the same state of affairs in atomic and nuclear physics. The hydrogen atom consists of an electron and a proton, but it can exist in states of different energy. The excited states of the hydrogen atom decay by emitting photons, leaving hydrogen in the ground state. Similarly, nuclei can be in excited states. So we should not be surprised that a system of three quarks can have a number of energy levels, like an atom or a nucleus. And in this particular case the heavier particle Σ^0 does in fact decay very quickly to produce Λ^0:

$$\Sigma^0 \longrightarrow \Lambda^0 + \gamma$$

We do not have much time to elaborate on the quark model. The important thing to remember is where the 'search for fundamental particles' has led in this Unit. We started with only two baryons—the proton and the neutron. In the last thirty years, many more have been discovered, making it difficult to believe that *any* baryon is a fundamental particle. The patterns of baryons, which led to the successful prediction of Ω^-, suggest that the familiar proton and neutron are intimately related to the unstable and rather exotic baryons that can be created by cosmic rays or in high energy physics laboratories. The quark model is an attempt to explain this diversity of hadrons in terms of new fundamental particles. So we have ended up with a model that says that an atom of hydrogen is made of an electron, two up quarks and one down quark. But only by puzzling about the phenomena of high energy physics could we be led to this new answer to the old question: what is matter made of? The interplay of theory and experiment, described in Radio programme 15, continues to produce new surprises!

Before leaving the quark model, there are two obvious and important questions that cannot be avoided. What are *mesons* made of? Has anyone ever *detected* quarks?

antiquark

First of all, let's think about the mesons. Mesons have $B = 0$, so there is no way we can build them using only the quarks with $B = \frac{1}{3}$. That meant that the quark model of Gell-Mann and Zweig had to have some more ingredients. These ingredients are called antiquarks, and they form the pattern of Figure 18. When we chose the quarks to correspond to the pattern of Figure 17, we decided to have the triangle pointing downwards. The antiquarks of Figure 18 correspond to making the other choice—a triangle pointing upwards. The quark model of mesons is then specified as follows:

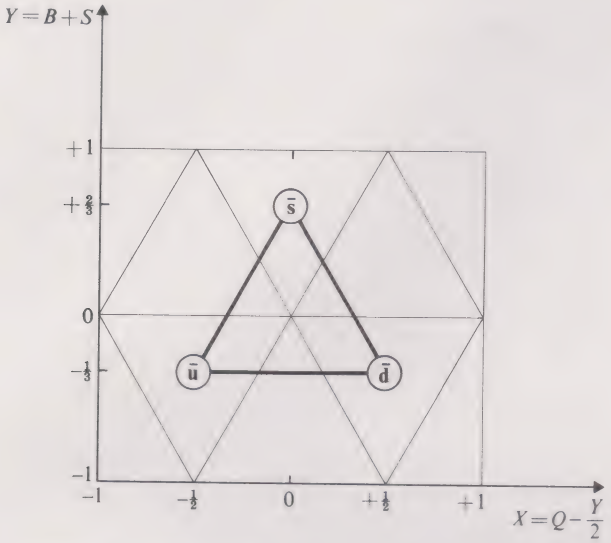

FIGURE 18 Three antiquarks.

Quark model of mesons

(a) As well as the three quarks u, d, s, there are three antiquarks: ū, d̄, s̄.

(b) The quantum numbers of the antiquarks are opposite to those of the quarks:

antiquark	Q	B	S	quark	Q	B	S
ū	$-\frac{2}{3}$	$-\frac{1}{3}$	0	u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
d̄	$+\frac{1}{3}$	$-\frac{1}{3}$	0	d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
s̄	$+\frac{1}{3}$	$-\frac{1}{3}$	+1	s	$-\frac{1}{3}$	$+\frac{1}{3}$	−1

(c) A meson consists of one quark and one antiquark.

We can now identify the mesons you have met with combinations of a quark and an antiquark. This is done in Table 8.

Incidentally, it did not surprise physicists that Gell-Mann and Zweig had to have antiquarks as well as quarks in their model. It is a general principle, which has been proved using the ideas of quantum theory and special relativity, that for every type of charged particle there must exist an *antiparticle* with the *opposite*

TABLE 8 A meson is made of a quark and an antiquark

Combination	B	Q	S	Mesons	
$(u\bar{s})$	0	+1	+1	K^+	K^{*+}
$(d\bar{s})$	0	0	+1	K^0	K^{*0}
$(u\bar{d})$	0	+1	0	π^+	ρ^+
$(u\bar{u})$, $(d\bar{d})$, $(s\bar{s})$	0	0	0	π^0, η^0	ρ^0, ω^0
$(d\bar{u})$	0	−1	0	π^-	ρ^-
$(s\bar{d})$	0	0	−1	$\bar{K}^0$	$\bar{K}^{*0}$
$(s\bar{u})$	0	−1	−1	K^-	K^{*-}

quantum numbers. You have met an example of an antiparticle in this Unit: the positron is the antiparticle of the electron. The proton too has its antiparticle: the antiproton, which was first detected in 1955. Other examples of particle–antiparticle pairs are (K^-, K^+), (π^-, π^+), (μ^-, μ^+). In the interests of simplicity, we have avoided discussing antibaryons, such as the antiproton, so far. But it is easy to fit an antibaryon into the quark model: it must be made out of three antiquarks.

8.2 Where are the quarks?

So now we have a model of *all* the hadrons. But has anyone ever found a quark? It is all very well to say that a proton is made of three quarks, but can you take it to bits and detect the individual building blocks? After the quark model was formulated in 1964, physicists searched very hard for evidence of particles with fractional charge. *But none were found*! Quarks have been hunted for in many experiments performed in many different ways. They have been looked for in cosmic rays, at high energy physics laboratories, in moon rocks, in oysters from the sea-bed, on metal spheres, indeed practically everywhere imaginable! Occasionally, evidence of fractionally charged particles has been claimed in an experiment, but confirmation has not been provided by other, comparable experiments. At the time of writing (1978) there is no clear evidence in favour of the existence of individual fractionally charged particles, and there is a great deal of evidence to suggest that, if fractionally charged particles exist, they are *very* rare and *very* hard to produce. Now it may be that by the time you study this Unit quarks will have been detected (in which case you will undoubtedly have heard about it from the newspapers, television or your tutor!). But it is fair to say that the expectation of the great majority of high energy physicists is that fractionally charged particles will *not* be detected in the next few years. Having looked so hard for them for the last 15 years, physicists don't expect to find them soon, if at all. This prejudice may be wrong, but it is certainly strong.

You might think that this conspicuous failure to detect particles with the properties attributed to quarks would have killed the model stone dead by now. But, ironically, the continued absence of individual quarks in the detectors of experimenters has gone hand-in-hand with a growing list of successful predictions and explanations made by theorists who persist in using quark models. There is not time to tell you much about the successes of the quark model, but one example merits a special mention.

If you think back to Unit 10, you should remember how Rutherford arrived at the idea that the atom has a nucleus. Alpha-particles aimed at a gold target were occasionally deflected through very large angles, much larger than could be explained by a continuous distribution of charge. The 'discovery' of the atomic nucleus was actually the discovery that the scattering of alpha-particles by gold was just what would be expected on the hypothesis that an atom of gold contained one particle with charge $Q = 79$ (in the units we are using here). An analogous state of affairs exists in high energy physics. It has been found that the scattering of high energy electrons, muons and neutrinos, by the protons and neutrons contained in any target, is very much in accord with what would be expected on the hypothesis that a proton contains three quarks, with charges

$Q = +\frac{2}{3}$, $+\frac{2}{3}$ and $-\frac{1}{3}$, and a neutron contains three quarks, with charges $Q = +\frac{2}{3}$, $-\frac{1}{3}$ and $-\frac{1}{3}$. If you believe in nuclei, you can 'measure' their charges in the way Rutherford and Chadwick did. If you believe in quarks, you can 'measure' their charges with high energy leptons. One of the remarkable successes of the quark model is that the charges which were assumed by Gell-Mann and Zweig in 1964 seem to be just those that give good predictions for experiments on the scattering of high energy leptons by hadrons, performed about a decade later.

8.3 Summary: a puzzling success

At present the claim of high energy physicists is that hadrons behave very much *as if* they were made of quarks. But individual quarks have not been detected directly, in the way that electrons or muons have been detected (using a bubble chamber, for example). That is the puzzle that preoccupies many high energy physicists at present. It is possible that the puzzle may disappear if someone detects a quark directly and unambiguously, but we have indicated that most physicists consider that unlikely. It is also unlikely that the quark model will be abandoned as a working hypothesis of the structure of hadrons; it has proved too resilient in the past to be put aside lightly. What seems more likely is that physicists will have to learn to live with what appears at present to be a paradox:

hadrons behave as if they are made of quarks of fractional charge;

hadrons cannot be broken down into particles of fractional charge, even in the highest energy collisions that have been studied.

It may be that this puzzle will only be solved after another revolution of scientific thinking, as profound as that which had to occur before physicists could live with the ideas of quanta behaving as *both* particles and waves.

Now check that you can recall features of the quark model (Objective 9).

SAQ 10 Which of the following statements correctly describe features of the quark model? (*Select four items from the key.*)

A A baryon consists of three quarks.

B A meson consists of three quarks.

C A meson consists of a quark and an antiquark.

D The quantum numbers of a baryon can be calculated from the quantum numbers of the quarks of which it is made.

E Individual quarks are produced by the collisions of hadrons.

F The quark model helps one to understand the scattering of leptons by hadrons.

G The quark model helps one to understand why fractionally charged particles have not been detected in bubble chambers.

9 Charm

The idea that hadrons are made of quarks has recently led to an important prediction: the prediction of a new property of hadrons, which has been called *charm*. Charm is a property rather like strangeness. It is described by a quantum number C, which has the value zero for all the hadrons you have met, but recently charmed hadrons with $C = +1$ and $C = -1$ have been discovered. This situation is reminiscent of the situation in Section 5, where you started knowing only about hadrons with $S = 0$, but then learned about strange hadrons with $S = +1$, -1, -2 and -3. Charm is also like strangeness in that it is conserved in strong interactions but can change by one unit in weak decays. But charm and strangeness differ greatly in the ways that they were *discovered*.

charm C

charmed hadron

conservation of C

The idea of strangeness came only *after* the discovery of 'strange' hadrons, but the idea of charm came *before* the discovery of 'charmed' hadrons. The story of charm is rather like the story of strangeness told in *reverse*.

To illustrate this we give a brief summary of what you have learnt about strangeness and quarks, in five short chapters, presented in true historical sequence but numbered in reverse order. Then we give a thumbnail sketch of the story of charm, also in five short chapters, numbered in the usual way.

By comparing chapters with the same number you should be able to get a good idea of why we say that charm is very much like strangeness, but that the discovery of charm involved a quite different sequence of events from the discovery of strangeness.

Strangeness

CHAPTER 5 Strange hadrons were discovered, in reactions which could not be understood using the ideas of baryon number (B) and charge (Q) alone. (Sections 5.4–5.7)

CHAPTER 4 Hadrons were assigned a strangeness quantum number (S) in order to explain the fact that only certain reactions and decays were found to occur. Patterns were revealed when hadrons were classified according to B, Q and S. (Sections 5.6 and 6)

CHAPTER 3 One more baryon (Ω^-) was predicted, on the basis of these patterns, and was subsequently discovered. (Section 7)

CHAPTER 2 The patterns of hadrons suggested a model that involved *three* types of quark, one of which—the strange quark (s)—carried strangeness. (Section 8.1)

CHAPTER 1 Many processes could then be better understood in terms of a *three*-quark model. (Section 8.2)

Charm

CHAPTER 1 It was suggested that there might be a *fourth* type of quark.

CHAPTER 2 Much larger patterns of hadrons were expected in a *four*-quark model. These patterns involved new hadrons, containing a new quark (c), as well as the old hadrons built out of u, d and s. But no such hadrons had been discovered.

CHAPTER 3 One more meson (ψ) was discovered, with properties which suggested that it might contain the *fourth* type of quark.

CHAPTER 4 Encouraged by this discovery, many physicists began to take the idea of a *four*-quark model seriously. That meant that hadrons should be classified according to *four* quantum numbers: B, Q, S and C, where C was a new property of hadrons, called charm, which was needed because of the *fourth* quark. All known hadrons had $C = 0$, but the existence of charmed hadrons with $C \neq 0$ was confidently predicted. Possible reactions and decays were suggested.

CHAPTER 5 Charmed hadrons were discovered, with properties that were in good agreement with the predictions of the *four*-quark model.

In Sections 9.1–9.5 we have tried to put a little flesh on the bare bones of these five chapters of the story of charm. But the details that follow are much less important than the outline given above.

> **Study comment** Your objective in studying Sections 9.1–9.7 should be to identify examples of the roles played by experimental discovery and theoretical prediction in the development of high energy physics (Objective 10). You have already met several examples of unexpected discoveries and of successful predictions (e.g. the discovery of strange hadrons and the prediction of omega minus). The chief reason for including the story of charm in this Course is to show the continuing interplay of experiment and theory at the frontiers of science. But we do not have the space to give (and you probably do not have the time to study) an account of charm and the four-quark model in the same detail as the account of strangeness and the three-quark model given in Sections 5–8. So be prepared for a more con-

densed presentation in the remainder of Section 9 and please remember that it is only the general features of the story that you are expected to retain (as you will see when you get to SAQs 11–13 in Section 9.7). The TV programme 31 and the associated *Broadcast Notes* give additional help in understanding charm and should communicate some of the excitement experienced by physicists in the period 1974–6.

9.1 Leptons and quarks

We have hardly mentioned the leptons since Section 4.4. Many new hadrons have been discovered since pions were first found to be produced by cosmic rays, but the number of leptons has grown much more slowly. The only new development that concerns us, in the period 1950–1974, is the discovery that there are *four* different types of neutrino. You know from Section 4.3 that two neutrinos are produced in μ^- decay and two are produced in μ^+ decay. It turns out that these four neutrinos are *all different*:

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

The differences between the neutrinos are revealed by their weak interactions with protons and neutrons:

$$\nu_e + n \longrightarrow p + e^-$$

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

$$\nu_\mu + n \longrightarrow p + \mu^-$$

$$\bar{\nu}_\mu + p \longrightarrow n + \mu^+$$

You need not try to remember which type of neutrino reacts in which way. The important thing is that there are four types, one for each type of *charged* lepton.

At present leptons are regarded as *fundamental* particles: there is no indication that they are made out of simpler particles. That means that today the physicist's answer to the question 'What is matter made of?' is the following.

> The fundamental particles are believed to be leptons, quarks, antiquarks, and a few particles associated with the forces between them (of which the photon is the only one so far detected).

In 1964, after the formulation of the quark model, the list of 'fundamental' particles was as follows:

TABLE 9 Fundamental particles and their charges (1964)

LEPTONS	ν_e 0	e^- -1	ν_μ 0	μ^- -1	$\bar{\nu}_e$ 0	e^+ $+1$	$\bar{\nu}_\mu$ 0	μ^+ $+1$
QUARKS	u $+\frac{2}{3}$	d $-\frac{1}{3}$		s $-\frac{1}{3}$				
ANTIQUARKS					$\bar{u}$ $-\frac{2}{3}$	$\bar{d}$ $+\frac{1}{3}$		$\bar{s}$ $+\frac{1}{3}$

PHOTON	γ 0

We have drawn up Table 9 in a way which may suggest to you an answer to the following questions:

> How many more quarks and antiquarks would you have to 'invent' to get more symmetry between leptons, on the one hand, and quarks and antiquarks, on the other? What charges would you assign to them?

Several physicists asked themselves these questions. Their answers were probably the same as yours:

> If there were a fourth quark c, with $Q = +\frac{2}{3}$, and a fourth antiquark $\bar{c}$, with $Q = -\frac{2}{3}$, the appearance of Table 9 would be improved, as indicated in Table 10.

TABLE 10 Fundamental particles and their charges (1974)

LEPTONS	ν_e 0	e^- -1	ν_μ 0	μ^- -1	$\bar{\nu}_e$ 0	e^+ $+1$	$\bar{\nu}_\mu$ 0	μ^+ $+1$
QUARKS	u $+\frac{2}{3}$	d $-\frac{1}{3}$	c $+\frac{2}{3}$	s $-\frac{1}{3}$				
ANTIQUARKS					$\bar{u}$ $-\frac{2}{3}$	$\bar{d}$ $+\frac{1}{3}$	$\bar{c}$ $-\frac{2}{3}$	$\bar{s}$ $+\frac{1}{3}$

PHOTON	γ 0

Now physicists are concerned with more important things than merely improving the appearance of tables: they are concerned with measuring and understanding or predicting the results of experiments. But it so happened that in the period 1964–1974 there were measurements of the weak decays of certain hadrons that were difficult to understand because they differed from the predictions of the three-quark model. The idea of charm resulted from the realization that some of the difficulties might be solved if there were a fourth quark and a fourth antiquark. The proponents of this idea coined the name *charm quark* for this hypothetical fourth ingredient of hadrons. It was claimed that not only was Table 10 more 'charming' in appearance than Table 9, but that this new addition would solve some outstanding problems 'like a charm'.

9.2 New patterns

Now for the second chapter of the story: what patterns of hadrons would be expected in a *four*-quark model?

It is important to realize that this new *four*-quark model involves only a fourth type of building block. The rule that a baryon contains three quarks was *not* changed. Nor was the rule that a meson contains a quark and an antiquark. An analogy may help here. The suggestion was that physicists had been rather like card players trying to play with a pack containing only diamonds, hearts and spades. The proposal was to increase the number of suits, by including clubs in the game. But the rule that a hand (corresponding to a baryon) must contain three cards was *not* changed. If you increase the number of suits, but leave the rules unchanged, there will be more ways of dealing a hand with three cards in it (corresponding to more baryons).

four-quark model of hadrons

Four-quark model of hadrons

(a) There are four types of quark and four types of antiquark.

(b) Their quantum numbers* are as follows:

quark	Q	B	S	C	antiquark	Q	B	S	C
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0	$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1	0	$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$+1$	0
c	$+\frac{2}{3}$	$+\frac{1}{3}$	0	$+1$	$\bar{c}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0	-1

(c) A baryon consists of three quarks and a meson consists of a quark and an antiquark.

* These are the quantum numbers that are shown in TV programme 31.

These are the ingredients of the four-quark model. We now have another quark c with $Q = +\frac{2}{3}$. Another quantum number is needed to distinguish the charm quark c from the up quark u, in the same way that strangeness distinguishes the strange quark s from the down quark d. This new quantum number was called *charm* and was given the symbol C. Note that the charm quark was assigned $C = +1$, so that the charm of a baryon is equal to the number of charm quarks it contains. (The strangeness of a baryon is equal to *minus* the number of strange quarks it contains, because it had originally been decided to assign $S = +1$ to the K^+ meson, long before quarks were thought of.)

In Table 11 you will find the quantum numbers of all the possible types of *meson* allowed in the four-quark model. The mesons you have already met do *not* contain charm quarks or antiquarks, but the symbols printed in red correspond to predicted new mesons which contain a charm quark or a charm antiquark. Before November 1974 there was no evidence to suggest that these new mesons (or any new baryons) actually existed. So you can see that that idea of a fourth quark brought with it many dramatic predictions.

To show the patterns made by hadrons in the four-quark model we need another dimension, which is why we are showing them in TV programme 31. The two-dimensional patterns of the three-quark model—that you discovered in Section 6.2—are merely slices of the larger three-dimensional patterns of the four-quark model that are shown in TV programme 31.

TABLE 11 Mesons, old and new, in the four-quark model

Combinations						Mesons	
New	Old	B	Q	S	C	Old	New
$(c\bar{s})$		0	+1	+1	+1		F^+
$(c\bar{d})$		0	+1	0	+1		D^+
$(c\bar{u})$		0	0	0	+1		D^0
	$(u\bar{s})$	0	+1	+1	0	K^+ K^{*+}	
	$(d\bar{s})$	0	0	+1	0	K^0 K^{*0}	
	$(u\bar{d})$	0	+1	0	0	π^+ ρ^+	
$(c\bar{c})$	$(u\bar{u})$ $(d\bar{d})$ $(s\bar{s})$	0	0	0	0	π^0 η^0 ρ^0 ω^0	ψ
	$(d\bar{u})$	0	−1	0	0	π^- ρ^-	
	$(s\bar{d})$	0	0	−1	0	$\bar{K}^0$ $\bar{K}^{*0}$	
	$(s\bar{u})$	0	−1	−1	0	K^- K^{*-}	
$(u\bar{c})$		0	0	0	−1		$\bar{D}^0$
$(d\bar{c})$		0	−1	0	−1		D^-
$(s\bar{c})$		0	−1	−1	−1		F^-

9.3 One discovery

psi meson ψ

The real break-through came in November 1974. A meson called ψ (the Greek letter 'psi') was discovered in independent experiments at two of the high energy physics laboratories whose names you have already met: the Brookhaven National Laboratory, near New York, and the Stanford Linear Accelerator Center in California*. The details of these experiments need not concern us; what is important is the conclusion reached by physicists studying the properties of ψ. The ψ meson behaved quite differently from what would be expected in the *three*-quark model. But it fitted nicely into the *four*-quark model. Before the discovery of ψ, the idea of a fourth quark had been just one of a number of speculative theories, waiting for data to explain. After the discovery of ψ, it rapidly became most people's favourite way of trying to solve old problems and make new predictions.

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* The team on the West Coast chose the name ψ. The other team, on the East Coast, chose the name J. To indicate this, the name J/ψ has been used by some physicists. The 1976 Nobel Prize for physics was shared by Richter and Ting, the leaders of the two teams.

There is one more thing to say about ψ: it is *not* a charmed meson. The quantum numbers of ψ are $B = Q = S = C = 0$, so it is neither strange nor charmed. The properties of ψ were explained by assuming that it contained a charm quark (c) and a charm antiquark ($\bar{c}$). Its existence, therefore, depends upon the existence of the fourth quark, even though the charm of ψ is zero.

9.4 Many predictions

If you look back at Chapters 1–4 of the story of charm, at the beginning of Section 9, you will see that there is not much more to say about the predictions of the four-quark model.

In 1975 many physicists confidently expected that charmed hadrons would be quickly discovered. It was expected that charmed hadrons would not be produced singly in the collisions of known hadrons, just as strange hadrons are not produced singly in the collisions of non-strange hadrons. To conserve charm they would have to be made in pairs:

$$\begin{array}{lcccl} & \pi^- + p & \longrightarrow & n + D^+ + D^- & (\textit{strong}\ \text{interaction}) \\ C: & 0 + 0 & = & 0 + 1 - 1 & (\textit{conserves}\ \text{charm}) \end{array}$$

Similarly charmed D mesons should be produced in pairs in the collisions of positrons and electrons at high energy, which is an electromagnetic interaction that should also conserve charm:

$$\begin{array}{lcccl} & e^+ + e^- & \longrightarrow & D^+ + D^- & (\textit{electromagnetic}\ \text{interaction}) \\ C: & 0 + 0 & = & +1 - 1 & (\textit{conserves}\ \text{charm}) \end{array}$$

But in the *weak* interactions of neutrinos it was expected that charmed hadrons could be produced singly, because it was believed that charm, like strangeness, could change by one unit in a weak process.

$$\begin{array}{lcccl} & \nu_\mu + p & \longrightarrow & \mu^- + p + D^+ & (\textit{weak}\ \text{interaction}) \\ C: & 0 + 0 & \neq & 0 + 0 + 1 & (\text{charm}\ \textit{changes}\ \text{by one unit}) \end{array}$$

It was expected that the charmed D^+ and D^- mesons would decay *weakly*, since charm could change by one unit in a weak decay, again in analogy with strangeness. In fact, decays such as:

$$\begin{array}{lcccl} & D^+ & \longrightarrow & K^- + \pi^+ + \pi^+ & (\textit{weak}\ \text{decay}) \\ B: & 0 & = & 0 + 0 + 0 & (\text{baryon number}\ \textit{conserved}) \\ Q: & +1 & = & -1 + 1 + 1 & (\text{charge}\ \textit{conserved}) \\ S: & 0 & \neq & -1 + 0 + 0 & (\text{strangeness}\ \textit{changes}) \\ C: & +1 & \neq & 0 + 0 + 0 & (\text{charm}\ \textit{changes}) \end{array}$$

were predicted. But there was a snag. It was expected that charmed hadrons would be appreciably *heavier* than their strange cousins. (It is now known that the charmed D^+ meson has a mass which is nearly four times that of the strange K^+ meson.) In very general terms, heavier hadrons are more difficult to produce (because more energy is needed) and decay faster (because more energy is released). So it was considered unlikely that tracks of charmed hadrons would be found in bubble-chamber photographs. Even if they could be produced travelling at high speeds (which would slow down their decay, according to the principle that 'moving clocks run slow'), it was doubtful whether charmed hadrons would live long enough to travel as much as a millimetre before decaying, certainly not long enough to leave a nice trail of bubbles in liquid hydrogen. So a different technique was needed to provide *visual* evidence of the existence of these new hadrons, and it seemed that the rather 'old-fashioned' technique of photographic emulsions, mentioned in Section 4.3, might do the job.

9.5 Confirmation

In the period 1976–8, many predictions of the four-quark model were confirmed. New hadrons, produced in strong, electromagnetic and weak interactions, have been detected, with the properties predicted for charmed hadrons. The weak decays of D^+ and D^- have been confirmed.

The first *visual* evidence of the existence of a new hadron, which is believed to be charmed, was provided by the emulsion photograph of Figure 19. This has been interpreted as showing the production of a charmed hadron at A, in the weak interaction of a neutrino, followed by a weak decay at B. The length of the track from A to B is only 0.2 mm—too short to be detected in a bubble-chamber photograph, but visible when a photographic emulsion is developed and viewed under a microscope. The picture of Figure 19 was published in a paper whose title page is reproduced in Figure 20. This title page should give you an idea of what we mean when we speak of a *team* of experimenters. If you look closely you will see that the Open University was represented in this team. Indeed, more recently (August 1979), evidence of the existence of a neutral charmed particle was found in photographic emulsion that had been exposed to a neutrino beam at CERN and scanned at Walton Hall.

FIGURE 19 A possible track of a charmed hadron in emulsion.

9.6 A note of warning

You might think that after November 1974 high energy physicists entered a period of continuing confirmation of the *four*-quark model, free for a while from the unexpected surprises that had been so common in the previous two decades. But Nature had a few tricks up her sleeve.

In 1975 a *new lepton* was discovered, totally unexpectedly. This was ironical, because much of the impetus for the four-quark model came from the pattern of leptons of Table 10. The existence of another lepton upset the applecart yet again and has led physicists to devise even more complicated models involving *five* or *six* quarks. In 1977 the first indications were found of hadrons that could not be fitted into the *four*-quark model.

It may well be that the studies of high energy physics are in process of revealing a new diversity—the diversity of leptons and quarks. The diversity of chemical substances is now understood in terms of a smaller number of elements. The diversity of elements is now understood in terms of electrons, neutrons and protons. The diversity of hadrons, related to neutrons and protons, is partially understood in terms of a smaller number of quarks. Maybe the next question should be:

Why are there so many quarks and leptons?

This question and the older question:

Why can leptons be observed in isolation but quarks apparently not?

should keep physicists busy for a few years!

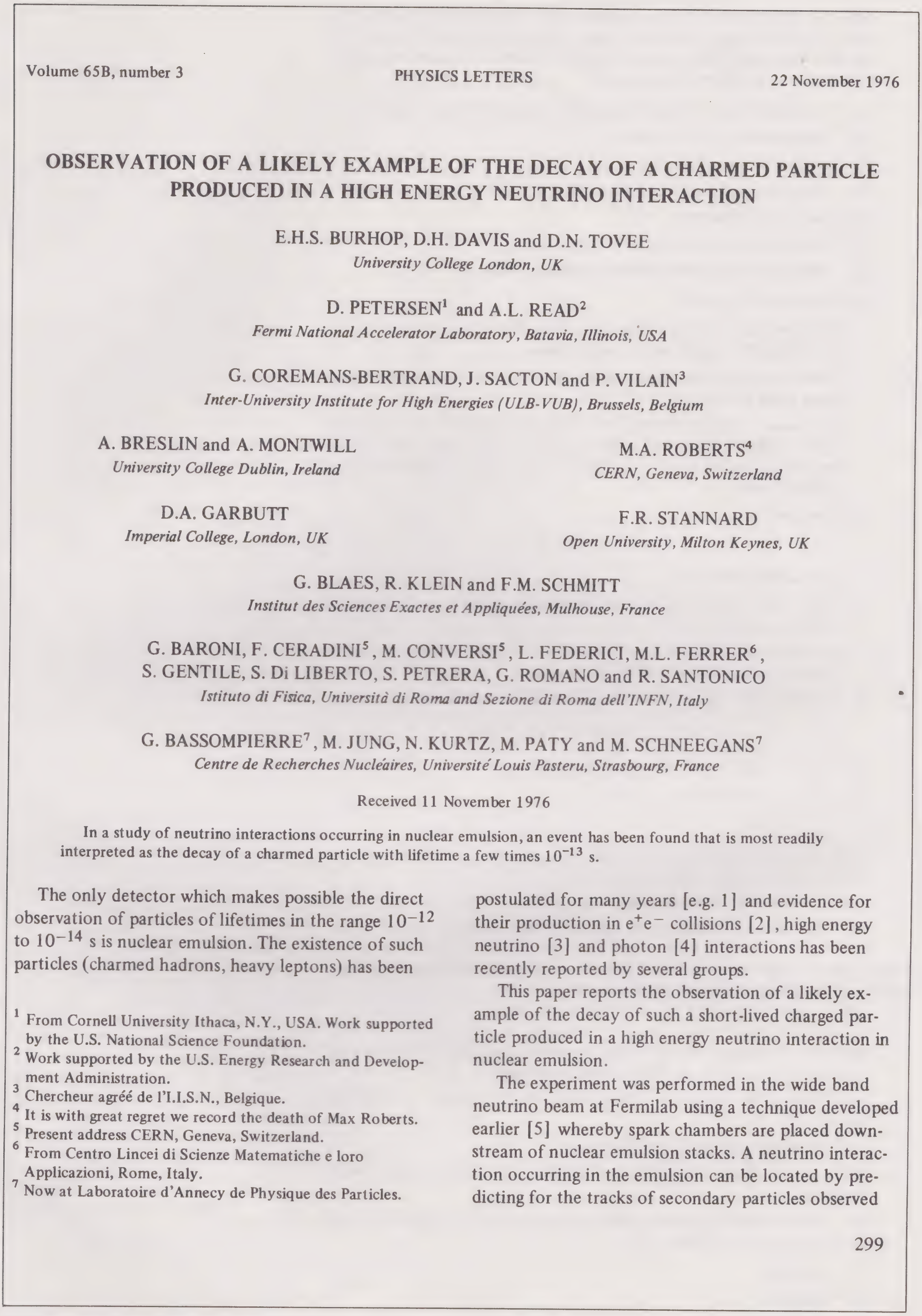
9.7 Summary: discovery, prediction and confirmation

At the beginning of Section 9 we gave the story of charm in outline. Charm is like strangeness: a quantum number of hadrons carried by one of the quarks of which hadrons are made. It is conserved in strong interactions, but can change in weak interactions and decays.

It is probably a good idea to reread the outlines of strangeness and charm, to remind yourself of the different historical order of their discovery. In Figures 21 and 22 you will find an even more abbreviated summary that shows the interplay of theory and experiment.

Figs. 21 and 22 are on p. 65.

Now see if you can identify examples of the roles played by experimental discovery and theoretical prediction in the development of high energy physics, as presented in the Unit (Objective 10).



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OBSERVATION OF A LIKELY EXAMPLE OF THE DECAY OF A CHARMED PARTICLE PRODUCED IN A HIGH ENERGY NEUTRINO INTERACTION

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In a study of neutrino interactions occurring in nuclear emulsion, an event has been found that is most readily interpreted as the decay of a charmed particle with lifetime a few times 10^{-13} s.

The only detector which makes possible the direct observation of particles of lifetimes in the range 10^{-12} to 10^{-14} s is nuclear emulsion. The existence of such particles (charmed hadrons, heavy leptons) has been postulated for many years [e.g. 1] and evidence for their production in e^+e^- collisions [2], high energy neutrino [3] and photon [4] interactions has been recently reported by several groups.

This paper reports the observation of a likely example of the decay of such a short-lived charged particle produced in a high energy neutrino interaction in nuclear emulsion.

The experiment was performed in the wide band neutrino beam at Fermilab using a technique developed earlier [5] whereby spark chambers are placed downstream of nuclear emulsion stacks. A neutrino interaction occurring in the emulsion can be located by predicting for the tracks of secondary particles observed

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FIGURE 20 A team of experimenters.

SAQ 11 In the key (A–J) you will find a list of experimental results. For each of the theoretical claims (a–g) made below choose the item from the key that best supports the claim and decide whether the experimental result was originally predicted or unexpected.

(a) The rate of decay of unstable particles depends on their speed. C P

(b) A baryon with $S = -3$ exists. G P

(c) Inertia increases with speed. A P

(d) Some hadrons contain a strange quark.

(e) Mass is not conserved. B P

(f) Some hadrons contain a charm quark. F P

(g) Quarks are not produced when hadrons collide. E

KEY for SAQs 11 and 12

A Electrons have not been found travelling faster than $3 \times 10^8\,\mathrm{m\,s^{-1}}$, even using the biggest particle accelerators.

B Electrons and positrons can annihilate to produce electromagnetic radiation when they collide.

C K^+ mesons travelling through a bubble chamber at 99 per cent of the speed of light leave tracks which are (on average) *more than* twice as long as the tracks left by K^+ mesons travelling at 50 per cent of the speed of light.

D The reaction

$$\pi^+ + p \longrightarrow K^+ + p$$

has *not* been observed.

E There is no evidence of fractionally charged particles leaving tracks in bubble chambers.

F In 1976 a new particle was discovered that lived for long enough to leave a visible track in emulsion.

G In 1964 a new particle, Ω^-, was produced in the reaction

$$K^- + p \longrightarrow \Omega^- + K^+ + K^0$$

H The K^- meson is heavier than the π^- meson.

J There are more than eight leptons.

SAQ 12 (a) Select three items from the key above (A–J) for which *no* explanation has been offered in this Unit.

(b) Can you offer an explanation of any of these three results?

(c) If so, does your explanation lead to any new prediction?

Finally, try to make some informed guesses about future developments in the search for fundamental particles (Objective 11).

SAQ 13 Choose an item from the key below (A–E) that expresses your expectation about each of the following predictions (a–d).

(a) Fractionally charged particles will soon be detected in a bubble chamber.

(b) Yet more leptons will be discovered.

(c) Quark models will soon be abandoned by the majority of high energy physicists.

(d) The number of particles regarded as fundamental will again decrease, as it did in 1964 (see Figure 23).

A Certainly

B Probably

C Don't know

D Probably not

E Certainly not

FIGURE 21 From strange hadrons to three quarks.

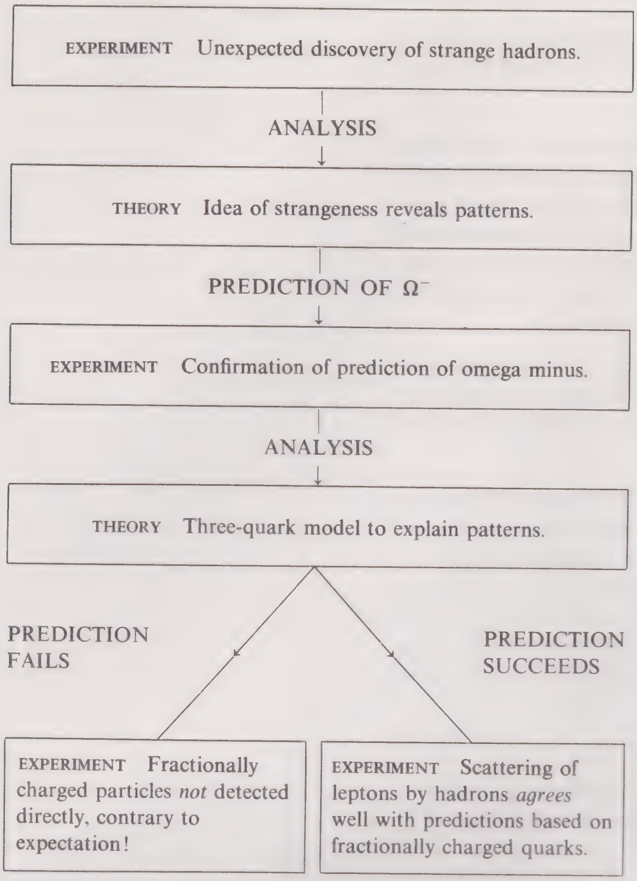
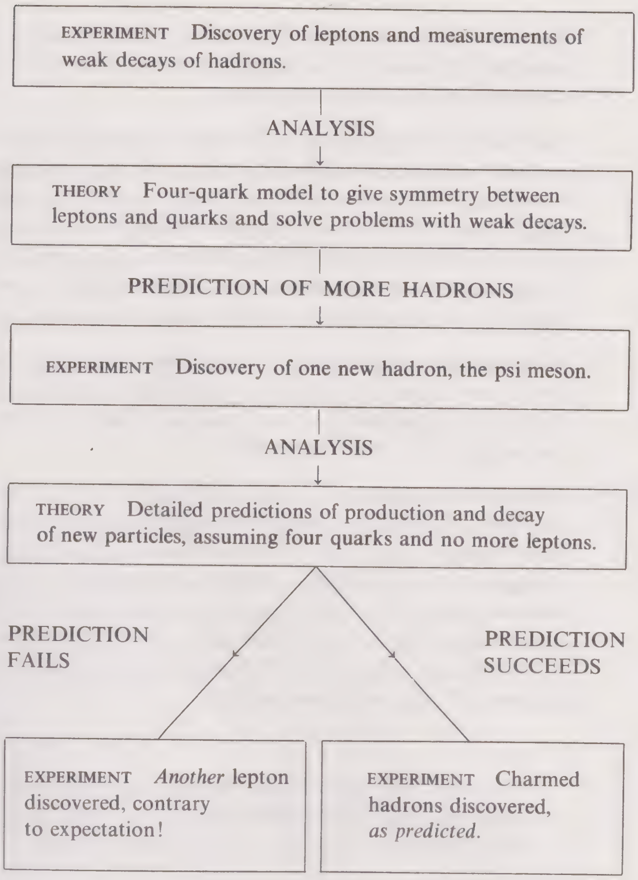

EXPERIMENT Unexpected discovery of strange hadrons.
ANALYSIS
THEORY Idea of strangeness reveals patterns.
PREDICTION OF Ω^-
EXPERIMENT Confirmation of prediction of omega minus.
ANALYSIS
THEORY Three-quark model to explain patterns.
PREDICTION FAILS
PREDICTION SUCCEEDS
EXPERIMENT Fractionally charged particles *not* detected directly, contrary to expectation!
EXPERIMENT Scattering of leptons by hadrons *agrees* well with predictions based on fractionally charged quarks.

FIGURE 22 From four quarks to charmed hadrons.


EXPERIMENT Discovery of leptons and measurements of weak decays of hadrons.
ANALYSIS
THEORY Four-quark model to give symmetry between leptons and quarks and solve problems with weak decays.
PREDICTION OF MORE HADRONS
EXPERIMENT Discovery of one new hadron, the psi meson.
ANALYSIS
THEORY Detailed predictions of production and decay of new particles, assuming four quarks and no more leptons.
PREDICTION FAILS
PREDICTION SUCCEEDS
EXPERIMENT *Another* lepton discovered, contrary to expectation!
EXPERIMENT Charmed hadrons discovered, *as predicted*.

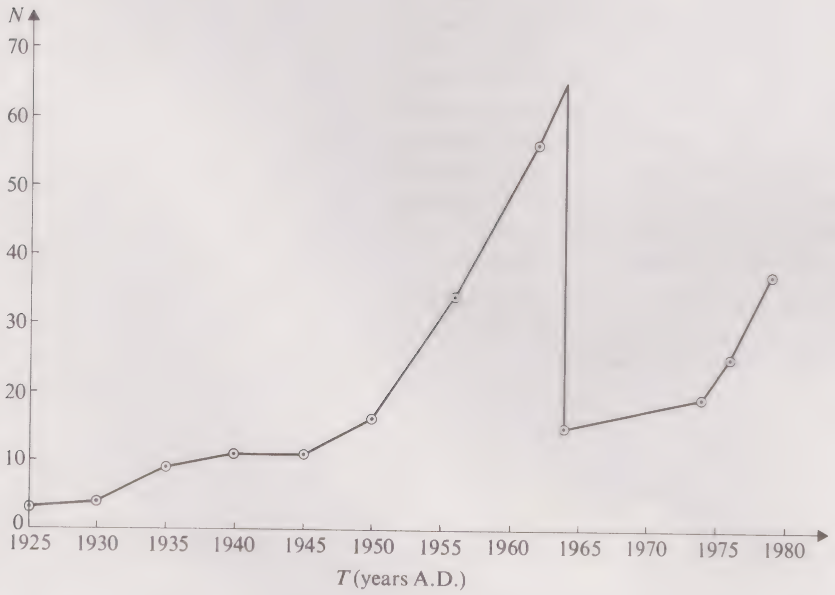


FIGURE 23 The number of supposedly fundamental particles (N) as a function of time (T). Note that at any time there may be considerable debate as to the value of N, but the general trend, indicated by joining the points by lines, is clear: N grew dramatically between 1945 and 1964, as many new hadrons were discovered, then fell dramatically, with the formulation of the quark model, and has been growing since 1964 as more leptons have been discovered and more quarks, antiquarks and particles associated with forces have been postulated. The tally in 1979 is $N = 37$, comprising 12 leptons, 6 quarks, 6 antiquarks, the photon (associated with electromagnetic forces), the 'graviton' (associated with gravitational forces), 3 'weak bosons' (associated with weak interactions) and 8 'gluons' (associated with strong interactions). Of these 37, only 11 have been detected as isolated particles: the photon, the eight leptons of Table 10 (p. 59), and two more leptons. The other 26 have so far not been detected directly, but have been postulated to explain the behaviour of known hadrons and leptons.

10 Summary

The best way to revise what you have learnt about the search for fundamental particles is to reread the Summary Sections 3.4, 4.5, 5.8, 6.3, 7.3, 8.3 and 9.7. Here is a brief outline of the whole story.

The studies of high energy physicists confirm Einstein's predictions that inertia increases with speed, that mass is not conserved, and that moving clocks run slow. For example, electrons from the Stanford linear accelerator do not travel anything like as fast as would be expected using Newton's laws of motion, particles of high mass can be created in the collisions of particles of lower mass, and muons in the atmosphere or K mesons in a bubble chamber travel farther than would be expected if it were not for Einstein's special theory of relativity.

When protons or electrons are accelerated to very high energies (corresponding to speeds very close to the speed of light) and made to collide with a target, new particles are produced, whose reactions and decays can be studied by taking photographs in a bubble chamber.

Many different hadrons are found at high energy physics laboratories. These are particles that interact strongly with each other to produce more hadrons. Some of these hadrons are called strange hadrons and a new quantum number—strangeness—is required to understand their reactions and decays. The patterns of hadrons led to the prediction of omega minus and to the formulation of the quark model, according to which hadrons are *not* fundamental particles, but are made of quarks (and antiquarks). Three types of quark were postulated to explain the patterns of hadrons known in 1964.

At present the fundamental particles are believed to be leptons, quarks, antiquarks and a few particles associated with the forces between them (of which the photon is the only one so far detected).

Leptons are produced in some of the weak decays of hadrons and they are distinguished from hadrons by not having strong interactions. It is not known how many types of lepton or how many types of quark there are. Between 1964 and 1974 a fourth quark was added to the quark model, so as to make the patterns of quarks and leptons correspond better and help solve some problems revealed by the weak decays of hadrons. This led to the prediction of charmed hadrons, containing the fourth quark. Charmed hadrons have recently been found, but this does not appear to be the end of the search for fundamental particles. Yet another lepton was discovered in 1975 and alreadv (1978) there are indications that five or six types of quark may be needed to understand the properties of hadrons.

One of the oustanding problems in physics at present is to explain why hadrons behave *as if* they were made of fractionally charged quarks, whereas such quarks have *not* been found to be produced in the collisions of hadrons.

Aims and Objectives

Aims

The Aims of this Unit are:

1 To describe three failures of Newtonian mechanics that were predicted by Einstein and have been confirmed by the studies of high energy physicists. (Objectives 1–3)

2 To discuss some of the hadrons and leptons that have been discovered in the last 50 years. (Objectives 4 and 5)

3 To explain how an unexpected diversity of hadrons was subsequently ordered using the quantum numbers B, Q and S. (Objectives 6 and 7)

4 To discover the patterns of hadrons that led to the prediction of the omega minus baryon and to the formulation of a three-quark model. (Objectives 8 and 9)

5 To summarize some of the interplay between theory and experiment in high energy physics, which is exemplified by the different stories of the discoveries of strangeness and charm. (Objectives 8–11)

Objectives

After you have finished this Unit you should be able to:

1 Recognize the limits to the validity of Newton's laws imposed by the increase of inertia with speed. (SAQ 1)

2 Relate changes in mass to changes in kinetic energy. (SAQs 2 and 6)

3 Understand the consequences for unstable particles of the fact that moving clocks run slow. (SAQ 3)

4 Distinguish between hadrons and leptons. (SAQ 4)

5 Distinguish between reactions of different strength. (SAQ 5)

6 Use the conservation of baryon number, charge, strangeness and charm, to decide whether a suggested process will occur. (SAQs 7 and 9)

7 Relate changes of strangeness and charm to rates of decay. (SAQs 8 and 9)

8 Predict the existence and quantum numbers of a hadron from the patterns made by other hadrons. (SAQ 9)

9 Recall the important features of the three-quark model of hadrons. (SAQ 10)

10 Identify examples of the roles played by experiment and theory in high energy physics. (SAQs 11 and 12)

11 Speculate on future developments in the search for fundamental particles. (SAQ 13)

ITQ answers and comments

ITQ 1 Your list should include the electron, proton, neutron and photon. You have not yet been given any reason to believe that these particles are made of simpler particles. There is also the positron, produced in β^+-decay (Unit 30). If you are an avid reader of footnotes you may remember a mention of a particle called a neutrino, in Section 6.3.1 of Unit 30. If not, do not worry; it will be discussed in Section 4.2 of this Unit. It does *not* follow that all the particles on your list are regarded as fundamental today. So far your study of modern physics has not progressed much farther than 1930. This Unit will take it as far as 1978.

ITQ 2 The speed is given by:

$$v = \frac{h}{m\lambda_{\text{dB}}}$$

$$= \frac{6.6 \times 10^{-34}\,\text{kg}\,\text{m}^2\,\text{s}^{-1}}{(6.6 \times 10^{-27}\,\text{kg}) \times (3.0 \times 10^{-15}\,\text{m})}$$

$$= 3.3 \times 10^7\,\text{m}\,\text{s}^{-1}$$

This is (a) 11 percent of the speed of light and (b) more than 10^5 times the speed of sound.

ITQ 3 The entire mass of the electron and positron ($1.022\,\text{MeV}/c^2$) is converted into the kinetic energy of the two photons. Each photon has an energy of 0.511 MeV, which is about two hundred thousand times the energy of a photon of visible light.

ITQ 4 A will expect $N/2 = 5\,000$. So $N = 10\,000$. But B will expect only 0.001 N = 10. B will get an impressive reminder that 'moving clocks run slow' when he detects 5 000 muons instead of the 10 he expected!

ITQ 5 Your list should include all the particles in Table 1 (p. 19). The particles in question are: (a) n, p (b) n, p, e^- (c) e^-, e^+, ν (d) γ (e) π^-, π^0, π^+, μ^-, μ^+ (f) μ^-, μ^+, ν (g) n, π^0, ν, γ.

ITQ 6 (a) You should have circled μ^+ and μ^- (muons), ν (neutrino), e^+ (positron) and e^- (electron).

(b) In (i) and (ii) the pions disappear. Pions are hadrons.

(c) In (iii) and (iv) the muons disappear. Muons are leptons.

(d) β-decay: (v) is an example of β^--decay; (vi) is an example of β^+-decay.

ITQ 7 (a) As was indicated in SAQ 5, pions can be produced by all three beams. But the *strong* interactions of a beam of protons with a target will produce pions more often than the *electromagnetic* interactions of a beam of muons. The *weak* interactions of neutrinos are certainly the worst way to produce pions! Use *protons*.

(b) Your best buy is the *muon* beam. Neutrinos do not have electromagnetic interactions and the strong interactions of protons will dominate over their electromagnetic interactions.

(c) This is where the *neutrinos* come into their own.

ITQ 8 Reaction (iv) is impossible because it does not conserve charge

$$\begin{array}{lcccc} & \pi^- + \text{n} & \not\longrightarrow & \text{p} + \pi^0 \\ Q\text{:} & -1 + 0 & \neq & +1 + 0 \end{array}$$

ITQ 9 Each pion must have $B = 0$. That is the only way that baryon number can be conserved:

$$\begin{array}{lccc} & \text{p} + \text{p} & \longrightarrow & \text{p} + \text{p} + \pi^0 \\ B\text{:} & 1 + 1 & = & 1 + 1 + 0 \end{array}$$

and similarly for π^+ and π^-.

ITQ 10 The η^0 particle cannot be a lepton, because it is produced directly in the strong interactions of hadrons. It must be a baryon or a meson. To decide which, denote the baryon number of η^0 by $B(\eta^0)$. Then:

$$\begin{array}{lcccl} & \pi^- + \text{p} & \longrightarrow & \text{n} + \eta^0 & \\ B\text{:} & 0 \;\; +1 & = & 1 + B(\eta^0) & \quad \text{so } B(\eta^0) = 0 \end{array}$$

That means that η^0 is a *meson* ($B = 0$).

ITQ 11 If you used the baryon numbers given on p. 32, and $B(\eta^0) = 0$ from ITQ 10, you should have found that (i), (ii) and (iii) are *impossible*. Only (iv) will be observed.

(i)
$$\begin{array}{lccc} & \Sigma^+ & \not\longrightarrow & \pi^+ + \eta^0 \\ B\text{:} & 1 & \neq & 0 \;\; +0 \end{array}$$

(ii)
$$\begin{array}{lccc} & \pi^- + \text{p} & \not\longrightarrow & \text{K}^- + \text{K}^+ \\ B\text{:} & 0 \;\; +1 & \neq & 0 \;\; +0 \end{array}$$

(iii)
$$\begin{array}{lccc} & \pi^+ + \text{p} & \not\longrightarrow & \text{p} + \text{p} \\ B\text{:} & 0 \;\; +1 & \neq & 1 + 1 \end{array}$$

(iv)
$$\begin{array}{lccc} & \pi^- + \text{p} & \longrightarrow & \Sigma^- + \text{K}^+ \\ B\text{:} & 0 \;\; +1 & = & 1 \;\; +0 \end{array}$$

ITQ 12 Starting with the values $S = 0$ for n, p, π^-, π^0, π^+ and $S = +1$ for K^+, conservation of strangeness tells you that:

(a) $0 + 0 = S(\Sigma^-) + 1$ so $S(\Sigma^-) = -1$ (as in text)

(b) $0 + 0 = S(\Sigma^0) + 1$ so $S(\Sigma^0) = -1$

(c) $0 + 0 = S(\Lambda^0) + 1$ so $S(\Lambda^0) = -1$

(d) $0 + 0 = S(\Sigma^+) + 1$ so $S(\Sigma^+) = -1$

(e) $S(\text{K}^-) + 0 = S(\Sigma^-) + 0$ so $S(\text{K}^-) = S(\Sigma^-) = -1$

(f) $S(\text{K}^-) + 0 = S(\Xi^-) + 1$ so $S(\Xi^-) = S(\text{K}^-) - 1 = -1 - 1 = -2$

(g) $S(\text{K}^-) + 0 = S(\Xi^0) + 1 + 0$ so $S(\Xi^0) = S(\text{K}^-) - 1 = -1 - 1 = -2$

Note that you need to know the result of (a) in (e), and the result of (e) in (f) and (g).

ITQ 13 The failures to conserve strangeness in the entries of Table 4b are expressed as follows:

(a) $0 + 0 \neq -1 + 0$ (as in text)

(b) $0 + 0 \neq 0 + 1$

(c) $0 + 0 \neq -1 + 0$

(d) $0 + 0 \neq -1 - 1$

(e) $1 + 0 \neq -1 + 0$

(f) $-1 + 0 \neq -2 + 0$

(g) $-1 + 0 \neq -2 + 1 - 1$

We have used the values of S from ITQ 12, which were derived from the analysis of Table 4a.

ITQ 14 Gell-Mann chose C: a baryon. If you are predicting a new hadron to fill the gap in the pattern of baryons of Figure 12, it had better be a baryon!

ITQ 15 Gell-Mann chose A: omega *minus*, to indicate that $Q = -1$. There are two ways you might arrive at this prediction. First of all Ω must lie on the same diagonal line as Δ^-, Σ^{*-} and Ξ^{*-} in Figure 12. All these particles have $Q = -1$. So should Ω. An equivalent way of arriving at the same conclusion is to use the coordinates of Ω from Figure 12.

$$X = Q - \frac{Y}{2} = 0 \qquad \text{so } Q = \frac{Y}{2}$$

$$Y = -2 \qquad \text{so } Q = -1$$

Except in ITQs 14–20, we shall indicate the charge $Q = -1$ by the symbol Ω^-. The minus sign has not been added to the symbol Ω in the ITQs, to allow you to make your own prediction.

ITQ 16 Gell-Mann chose E: $S = -3$, a value of strangeness that had never been observed previously. The reason is that Ω^- is a baryon with $B = 1$ (ITQ 14) and has a coordinate:

$$Y = B + S = -2$$

Hence

$$\begin{aligned} S &= Y - B \\ &= -2 - 1 \\ &= -3 \end{aligned}$$

ITQ 17 Gell-Mann predicted a mass corresponding to C. A value of roughly 1 670 MeV/c^2 seems reasonable, if you study how the masses of the other baryons increase as Y decreases in Figure 12:

		Mass	Difference
Δ^-	$Y = +1$	1 235	
			150
Σ^{*-}	$Y = 0$	1 385	
			145
Ξ^{*-}	$Y = -1$	1 530	
			140(?)
Ω^-	$Y = -2$	1 670(?)	

You might guess any value between 140 and 150 MeV/c^2 for the difference in mass between Ω^- and Ξ^{*-}. The prediction (1670 ± 30) MeV/c^2 is a cautious one.

ITQ 18 Gell-Mann knew that D was allowed by the quantum numbers $B = 1$, $Q = -1$, $S = -3$, but that the other suggestions were not.

A $\qquad K^- + p \not\longrightarrow \Omega^- + K^+$

S: $-1 + 0 \neq -3 + 1$ (strangeness *not* conserved)

B $\qquad K^- + p \not\longrightarrow \Omega^- + K^+ + K^+$

Q: $-1 + 1 \neq -1 + 1 + 1$ (charge *not* conserved)

C $\qquad K^- + p \not\longrightarrow \Omega^- + \Sigma^+ + K^0$

B: $0 + 1 \neq 1 + 1 + 0$ (*not* conserved)

S: $-1 + 0 \neq -3 - 1 + 1$ (*not* conserved)

D $\qquad K^- + p \longrightarrow \Omega^- + K^+ + K^0$ (strong interaction)

$$\left.\begin{aligned} B&: \; 0 + 1 = 1 + 0 + 0 \\ Q&: \; -1 + 1 = -1 + 1 + 0 \\ S&: \; -1 + 0 = -3 + 1 + 1 \end{aligned}\right\} \text{ (\textit{all} conserved)}$$

ITQ 19 Gell-Mann knew that C, D and E were allowed by $S = -3$ and $M(\Omega^-) = (1\,670 \pm 30)$MeV/$c^2$, but that A and B were forbidden by the rule that strangeness cannot change by more than one unit in a decay, and that F was forbidden if $M(\Omega^-)$ was less than $M(\Sigma^0) + M(K^-) = 1\,192 + 494 = 1\,686$ MeV/c^2. It is up to you whether you allow F. It is just allowed by a cautious prediction of the mass. But if you think that the method of ITQ 17 suggests $M(\Omega^-) = (1\,675 \pm 10)$ MeV/c^2 (a *less* cautious prediction) you can rule out F.

ITQ 20 Gell-Mann chose D, on the grounds that Ω^- would have the *weak* decays predicted in ITQ 19 and was *charged*. It would therefore be expected to leave a track between production and decay, in the same manner as you saw Σ^- leave a track when you studied stereophotograph No. 5 in Section 5.7. There is no reason to choose C, because Ω^- is *not* neutral. There is no reason to think that Ω^- might live appreciably longer than Σ^-, so why choose B? You should only choose A if you can think of a *strong* decay, conserving strangeness, which Ω^- might have. But its predicted mass was too *small* for it to decay into either of the following combinations of hadrons with $S = -3$.

$\Omega^- \not\longrightarrow \Xi^- + \bar{K}^0$ (*not* allowed)

S: $-3 = -2 - 1$

M: $1\,670 \pm 30 < 1\,321 + 498 = 1\,819$ (mass *cannot* increase)

$\Omega^- \not\longrightarrow \Xi^0 + K^-$ (*not* allowed)

S: $-3 = -2 - 1$

M: $1\,670 \pm 30 < 1\,315 + 494 = 1\,809$ (mass *cannot* increase)

Other combinations with $S = -3$ (such as $\Lambda^0 + K^- + \bar{K}^0$ or $p + K^- + K^- + \bar{K}^0$) are even more massive. So Ω^- was predicted to have only *weak* decays (in which S changes) and hence to leave a visible track.

SAQ answers and comments

SAQ 1 According to Newton's second law there should be a constant acceleration of $1\,\mathrm{m\,s^{-2}}$. That means that the speed should increase by $1\,\mathrm{m\,s^{-1}}$ every second, which leads to the following predictions:

A	$v = 1\,\mathrm{m s^{-1}}$	after one second
B	$v = 60\,\mathrm{m s^{-1}}$	after one minute
C	$v = 3.6 \times 10^3\,\mathrm{m\,s^{-1}}$	after one hour
D	$v = 3 \times 10^8\,\mathrm{m\,s^{-1}}$	after ten years
E	$v = 3 \times 10^9\,\mathrm{m\,s^{-1}}$	after a hundred years

The failure of Newton's second law would certainly be apparent after ten years (D). After ten years the speed *predicted* by Newton's second law is approximately equal to the speed of light. The *true* speed would be significantly less than the speed of light, because of the increase of inertia at high speeds. (In fact, Einstein's prediction is about 70 per cent of the speed of light.)

But the failure of Newton's second law would *not* be apparent after one hour (C). The predicted speed is only $3.6 \times 10^3\,\mathrm{m\,s^{-1}} = 8\,100$ m.p.h. As remarked on page 10, the increase of inertia is only about one part in 10^{10} at such a speed—far too small to lead to detectable effects.

Note that after a hundred years (E) the failure of Newton's second would be *very* apparent. The *predicted* speed is *ten times* the speed of light. The *true* speed would be *slightly less than* the speed of light.

SAQ 2 In the process of ionization there is a decrease in kinetic energy and hence an increase in mass, so the answer is (c). The changes in mass in atomic processes are too small to be detected, but the great success of Einstein's predictions, in the areas of nuclear and high energy physics, is sufficient to convince physicists that changes in kinetic energy are *always* accompanied by changes in mass, according to the formula $E = mc^2$.

SAQ 3 (a) The journey would take only 80 per cent of 150 years, i.e. 120 years, according to a clock on the rocket, even though it would take 150 years according to a clock on Earth.

(b) That means that the journey would take only 4 half-lives of the nuclei on the rocket, even though it would take 5 half-lives of nuclei left on Earth. Thus the number of grams remaining on the rocket would be:

$$32 \times (\tfrac{1}{2})^4 = \tfrac{32}{16} = 2$$

which is twice as much as would remain had the nuclei stayed on Earth.

SAQ 4 (a) It depends on the isotope of hydrogen. If we assume that neither of the hydrogen nuclei are ${}^2_1\mathrm{H}$ (deuterium) nuclei there are *two* hadrons in a hydrogen molecule: the two protons which are the ${}^1_1\mathrm{H}$ nuclei of the two atoms.

(b) No, the number of hadrons does not change in β-decay: an increase in the number of protons is always accompanied by a decrease in the number of neutrons, or vice versa.

(c) Two leptons are produced in β-decay: an electron and a neutrino in β^--decay, or a positron and a neutrino in β^+-decay.

(d) There are ten leptons in a water molecule: one electron for each hydrogen atom and eight for the oxygen atom.

(e) The number of hadrons in a water molecule is variable, because different naturally occuring isotopes of oxygen contain different numbers of neutrons. (The same applies to hydrogen, as indicated in (a).)

SAQ 5 *Most* pions will be produced by the *strong* interactions of the *protons*, such as (i). *Least* will be produced by the *weak* interactions of the *neutrinos*, such as (iii). The *muons* have *electromagnetic* interactions, such as (ii), which will produce pions more readily that (iii), but less readily than (i).

SAQ 6 The masses in MeV/c^2 can be calculated as follows:

(i) $M(\mathrm{e}^+) + 0.5 = 0 + 0 + 1.0 \qquad \text{so } M(\mathrm{e}^+) = 0.5$

(ii) $M(\mu^-) = 0.5 + 0 + 0 + 105.2 = 105.7$

(iii) $M(\mu^+) = 0.5 + 0 + 0 + 105.2 = 105.7$

(iv) $M(\pi^0) = 0 + 0 + 135.0 \qquad = 135.0$

(v) $M(\pi^-) = 105.7 + 0 + 33.9 \qquad = 139.6$

(vi) $938.3 + 938.3 = 938.3 + 939.6 + M(\pi^+) - 140.9$

$$\begin{aligned} \text{so } M(\pi^+) &= 140.9 + 938.3 - 939.6 \\ &= 140.9 - 1.3 \\ &= 139.6 \end{aligned}$$

Note that (vi) is the same calculation as was done on p. 13.

The lightest hadron (π^0) is heavier than the heaviest leptons (μ^- and μ^+).

SAQ 7 You should have crossed out (b), (c) and (f).

(b)
$$\left.\begin{array}{rccc} & \mathrm{p}+\mathrm{p} & \not\longrightarrow & \mathrm{p}+\pi^+ + \pi^+ + \pi^- \\ B: & 1+1 & \neq & 1 + 0 + 0 + 0 \end{array}\right\} \text{does } \textit{not} \text{ conserve } B$$

(c)
$$\left.\begin{array}{rccc} & \mathrm{p}+\mathrm{p} & \not\longrightarrow & \mathrm{p}+\mathrm{p}+\pi^+ \\ Q: & 1+1 & \neq & 1+1+1 \end{array}\right\} \text{does } \textit{not} \text{ conserve } Q$$

(f)
$$\left.\begin{array}{rccc} & \mathrm{p}+\mathrm{p} & \not\longrightarrow & \mathrm{p}+\Sigma^+ \\ S: & 0+0 & \neq & 0-1 \end{array}\right\} \text{does } \textit{not} \text{ conserve } S$$

SAQ 8 (a) The decays of π^0, η^0 and Σ^0 are *electromagnetic* decays in which *photons* are produced and strangeness is *conserved*. The half-lives are in the range $10^{-16} - 10^{-19}$ seconds.

(b) The decays of Δ^{++}, Δ^+, Δ^0, Δ^-, Σ^{*+}, Σ^{*0}, Σ^{*-}, Ξ^{*0} and Ξ^{*-} are *strong* decays in which only *hadrons* are produced and strangeness is *conserved*. The half-lives are of order 10^{-23} seconds.

(c) The remaining decays are *weak* decays.

(d) Some of the weak decays conserve strangeness (e.g. the decays of π^+ and n) but others do *not* (e.g. the decays of K^0 and Λ^0).

(e) The common characteristic is a half-life of order 10^{-10} seconds or longer. (An alterative way of deciding whether a decay is *weak* is to see whether it involves a change of strangeness *or* the production of a neutrino.)

SAQ 9 (a) The missing hadron is a *meson* with coordinates

$$X = Q - \frac{Y}{2} = +\tfrac{1}{2}$$

$$Y = B + S = +1$$

Its quantum numbers are therefore $B = 0$, $Q = 1$, $S = 1$. Its mass should be close to that of the other strange meson, K^{*0}, which belongs to the same family, i.e. 890 MeV/c^2. Such a particle exists and is called K^{*+}.

(b) Yes, this is a possible strong interaction of high energy π^+ mesons.

$$\pi^+ + \mathrm{p} \longrightarrow \Sigma^+ + \mathrm{K}^{*+} \qquad (\textit{strong}\ \text{interaction})$$

$$\left.\begin{array}{lcccc} B: & 0 & +1 & = & 1 & +0 \\ Q: & 1 & +1 & = & 1 & +1 \\ S: & 0 & +0 & = & -1 & +1 \end{array}\right\} \quad (\text{all } \textit{conserved})$$

(c) This decay conserves B, Q and S. It can and does occur:

$$\mathrm{K}^{*+} \longrightarrow \mathrm{K}^0 + \pi^+ \qquad (\textit{strong}\ \text{decay})$$

$$\left.\begin{array}{lccccc} B: & 0 & = & 0 & +0 \\ Q: & 1 & = & 0 & +1 \\ S: & 1 & = & 1 & +0 \end{array}\right\} \quad (\text{all } \textit{conserved})$$

(d) The particle will *not* live long enough to leave a detectable track. The decay given in (c) involves only *hadrons* and *conserves* strangeness, so it will be a *strong* decay. That means a half-life of only 10^{-23} seconds, which is much too short a time to allow the K^{*+} meson to travel far enough to leave a detectable trail of bubbles. Only charged particles that are stable (e.g. p or e^-) or have *weak* decays (e.g. Σ^- or K^+) leave detectable tracks in a bubble chamber.

SAQ 10 You should have selected A, C, D and F. B is incorrect because C gives the correct way of making mesons. E is incorrect because fractionally charged particles have *not* been detected. G is incorrect, because the quark model we have outlined does *not* explain why quarks have not been detected.

SAQ 11 (a) is a *prediction*, confirmed by C.

(b) is the *prediction* of Ω^-, confirmed by G.

(c) is a *prediction*, confirmed by A.

(d) is a way of understanding strangeness and hence D. But strangeness came *before* quarks, so D was originally an *unexpected* result.

(e) is a *prediction*, confirmed by B.

(f) is a way of understanding charm and hence F. In this case charm came *after* quarks, so F was *predicted*.

(g) is what you must conclude from E if you adopt the quark model, but E is a rather *unexpected* result if you believe firmly in quarks and have not got any understanding of why (g) should be the case.

SAQ 12 (a) No explanation has been offered for E, H and J.

(b) The Course Team has nothing further to say about E or J! But it might have occurred to you that H could be explained by a model in which the s quark is heavier than the d quark.

(c) It is difficult to think of any genuine prediction that could be made on the basis that the s quark is heavier than the d quark, using only the very qualitative formulation of the quark model presented in this Unit. Of course you can test this idea against *existing* data. (Is Λ^0 heavier than the neutron?) But can you think of an experiment or a measurement whose result you do *not* know and then make a *prediction* about it in advance, using this idea of quark masses? The Course Team could not think of a simple prediction along these lines. But maybe you can. If so, why not ask your tutor to try to find out whether any relevant data exist, or may become available soon?

SAQ 13 Only you can decide which answers best express your own expectations. But we hope that you have not chosen A or E from the key in many of your answers: certainty is not a healthy attitude of mind at the frontiers of science!

Here are the answers that a consensus of high energy physicists might give in 1978.

(a) D

(b) B or C

(c) D or E

(d) C

The safest bet is against (c); the quark model has proved very resilient since 1964. But perhaps the most intriguing question concerns (d). Who knows what Figure 23 will look like by the year A.D. 2000? Only time will tell. The search for fundamental particles is still in progress!

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Figure 1 Stanford Linear Accelerator Center, California; *Figure 2* University of Bristol Cosmic Ray Group; *Figure 5* CERN, Geneva; *Figure 13* Brookhaven National Laboratory, Long Island; *Figure 20* North-Holland Publishing Company.

TABLE 5 Twenty-five assorted hadrons (1962)

Symbol	Name	Mass/ MeV/c^2	B	Q	S	Half-life/ seconds	Main decay	Rough date of discovery
π^0	pi zero	135	0	0	0	0.6×10^{-16}	$\pi^0 \rightarrow \gamma + \gamma$	1950
π^+	pi plus	140	0	+1	0	1.8×10^{-8}	$\pi^+ \rightarrow \mu^+ + \nu$	1947
π^-	pi minus	140	0	−1	0	1.8×10^{-8}	$\pi^- \rightarrow \mu^- + \nu$	
K^+	K plus	494	0	+1	+1	0.9×10^{-8}	$K^+ \rightarrow \mu^+ + \nu$	1947–56
K^-	K minus	494	0	−1	−1	0.9×10^{-8}	$K^- \rightarrow \mu^- + \nu$	
K^0	K zero	498	0	0	+1	0.6×10^{-10}	$K^0 \rightarrow \pi^+ + \pi^-$	
$\bar{K}^0$	K zero bar	498	0	0	−1	0.6×10^{-10}	$\bar{K}^0 \rightarrow \pi^+ + \pi^-$	
η^0	eta zero	549	0	0	0	0.5×10^{-18}	$\eta^0 \rightarrow \gamma + \gamma$	1961
p	proton	938	1	+1	0	STABLE	NONE	1886
n	neutron	940	1	0	0	0.6×10^3	$n \rightarrow p + e^- + \nu$	1932
Λ^0	lambda zero	1 116	1	0	−1	1.8×10^{-10}	$\Lambda^0 \rightarrow p + \pi^-$	1951–3
Σ^+	sigma plus	1 189	1	+1	−1	0.6×10^{-10}	$\Sigma^+ \rightarrow p + \pi^0$	1953
Σ^0	sigma zero	1 192	1	0	−1	$\sim 10^{-19}$	$\Sigma^0 \rightarrow \Lambda^0 + \gamma$	1959
Σ^-	sigma minus	1 197	1	−1	−1	1.0×10^{-10}	$\Sigma^- \rightarrow n + \pi^-$	1953
Δ^{++}	delta double plus	1 235	1	+2	0	0.4×10^{-23}	$\Delta^{++} \rightarrow p + \pi^+$	1952
Δ^+	delta plus	1 235	1	+1	0	0.4×10^{-23}	$\Delta^+ \rightarrow p + \pi^0$	
Δ^0	delta zero	1 235	1	0	0	0.4×10^{-23}	$\Delta^0 \rightarrow n + \pi^0$	
Δ^-	delta minus	1 235	1	−1	0	0.4×10^{-23}	$\Delta^- \rightarrow n + \pi^-$	
Ξ^0	xi zero	1 315	1	0	−2	2.1×10^{-10}	$\Xi^0 \rightarrow \Lambda^0 + \pi^0$	1959
Ξ^-	xi minus	1 321	1	−1	−2	1.1×10^{-10}	$\Xi^- \rightarrow \Lambda^0 + \pi^-$	1953
Σ^{*+}	sigma star plus	1 385	1	+1	−1	1.3×10^{-23}	$\Sigma^{*+} \rightarrow \Lambda^0 + \pi^+$	1960
Σ^{*0}	sigma star zero	1 385	1	0	−1	1.3×10^{-23}	$\Sigma^{*0} \rightarrow \Lambda^0 + \pi^0$	
Σ^{*-}	sigma star minus	1 385	1	−1	−1	1.3×10^{-23}	$\Sigma^{*-} \rightarrow \Lambda^0 + \pi^-$	
Ξ^{*0}	xi star zero	1 530	1	0	−2	0.5×10^{-22}	$\Xi^{*0} \rightarrow \Xi^- + \pi^+$	1962
Ξ^{*-}	xi star minus	1 530	1	−1	−2	0.5×10^{-22}	$\Xi^{*-} \rightarrow \Xi^0 + \pi^-$	

Do NOT attempt to memorize any of these details.

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